Delay-/Disruption-Tolerant Networking State of the Art and Future Challenges

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Abstract

Networking for challenged environments, or Delay- and Disruption-Tolerant Networking as it is now most commonly referred to, has attracted great attention in the past few years by the networking research community. Connectivity disruptions, limited network capacity, energy and storage constraints of the participating, mobile devices and the arbitrary movement of nodes are only a few of the challenges that the protocol stack has to deal with. Clearly, current Internet protocols (i.e., the TCP/IP protocol stack) suffer and can fail under such conditions.

In this paper, we initially give the *DTN Problem Statement*; we contend that not all applications have the same requirements from the system and hence, equal (blind) treatment of all data packets will result in reduced network efficiency. Based on that we propose a *Design Position* for DTN protocols, which states that protocol design has to be done *proactively*, on the basis of the application's requirements.

We then survey the most recent contributions on the whole spectrum of Delay- and Disruption-Tolerant Networking, from the architectural and the application point of view down to the transport- and the network-layer of the emerging DTN protocol stack. We find that although not explicitly mentioned

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in most cases, research trends follow our Design Position. To the best of our knowledge this is the first study that discusses and evaluates research contributions from such a broad perspective. Finally, we highlight research challenges and open issues that require further investigation.

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1. Introduction

The term Delay-/Disruption-Tolerant Networking [1] has its roots in the InterPlaNetary (IPN) Internet [2]. Due to the extremely high propagation delays experienced when transferring data between different planets of our solar system, researchers and scientists identified the main difference between terrestrial and space communications: *the algorithms and protocols used for (deep-) space communications have to be delay-tolerant*. Moreover, due to the high bit error rates and the long-term disconnections experienced in such environments, the research field was also complemented with the term "disruption".

Later on, the networking research community identified opportunities for deployment of Delay-/Disruption-Tolerant Networks in the terrestrial (or the edges of the terrestrial) Internet as well (Figure 1). This new field of research has attracted a lot of attention lately, mainly due to its challenging characteristics. Intermittent connectivity, high mobility, unknown mobility patterns, energy and storage exhaustion comprise just a few of the potential issues that one may face in a DTN environment.

DTNs epitomize in a single research field all the problems the networking research community was concerned about until now. For example, routing was a different research topic than congestion control; application design was decoupled from the underlying transport or routing protocols and their principles; routing protocols would not need to take buffer management or queuing issues into consideration. These topics could be considered in isolation.

In DTNs such rules and assumptions have to be reconsidered. DTN nodes may consist of powerful laptop computers, but may also consist of tiny sensors. Resource heterogeneity will obviously have tremendous impact on the energy and storage resources of the corresponding nodes. Furthermore, the absence of end-to-end connectivity makes routing/forwarding and resource reservation decisions even more difficult to make. By and large, such issues have been investigated for wireless ad-hoc [3], [4] and/or mesh networks [5], [6], but again, in these environments end-to-end connectivity is assumed to exist when data transfers take place.

Research on DTN-related issues has already expanded and covers a wide variety of environments. For example, the IRTF [7] DTN Research Group [1] focuses mainly on Deep-Space communications and the *Bundle Protocol* (which is expected to be deployed in some terrestrial environments as well), while the broader DTN research community has investigated delay-tolerant communications for developing countries, vehicular networks and social networking, just to name a few[1]. Clearly, there is huge heterogeneity between different application environments as well as between the participating DTN-nodes and their resource availability. For instance, "line-of-sight" times (and therefore connectivity) for Deep-Space communications is known well in advance, hence routing is not much of an issue and becomes more of a scheduling and resource allocation problem. The case, however, is not the same for a vehicular DTN. That said, application metrics and service targets differ accordingly.

In this study, we argue that a framework should be officially established to categorize different deployment scenarios for DTNs; this framework should also incorporate the associated fundamental properties for each scenario/working environment and its corresponding applications. Based on that, researchers will be able to focus on specific algorithmic considerations in order to optimize performance accordingly. For example, the Deep-Space Network has different requirements and different targets from a vehicular DTN. In turn, a vehicular DTN is considerably different, architecture- and infrastructure-wise from an Un-

[1]Some people refer to *DTN* as the research conducted within the DTNRG [1] only and to *dtn* as the research of the broader (mainly academic) research community, similarly to the difference between the *Internet* and an *internet*. We note that herein, we refer to DTN as the general framework/research topic and point explicitly to DTNRG, whenever we refer to this group's efforts.

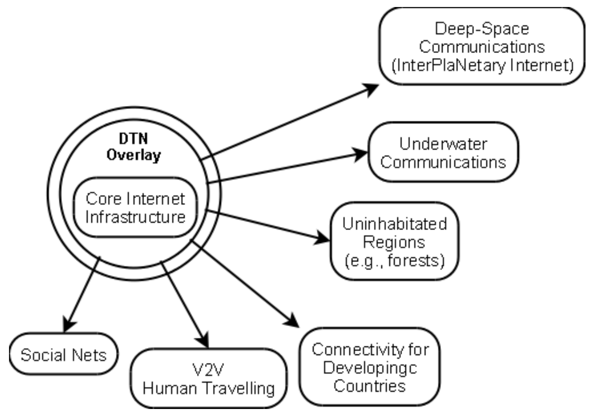

Figure 1: Geographical Distribution of Delay-Tolerant Networks

derwater DTN (Figure 1). Clearly, the corresponding applications attached to each DTN environment and their targets will differ considerably as well. Based on the above, we agree with the authors in [8], who *"Promote Tolerance for Delay-Tolerant Network Research"*. The authors pose and attempt to answer questions regarding the *applicability, viability and validity* of delay-tolerant networking research and its potential deployment. Among others, authors in [8] conclude that this new field of networking research requires tolerance before results are evident. We attempt to extend the considerations raised in [8] in order to add needed skepticism to aspects of DTN research, but in a broader perspective. The main contributions as well as the structure of this paper are as follows:

1. Initially, in Section 2, we present the problem that the DTN-protocol designer has to solve, following a top-down approach (i.e., as we observe it from the application's point of view). That is, given the unique characteristics of delay-/disruption-tolerant networks, we contend that not all applications have the same requirements.
2. Next, in Section 3, we differentiate between *Service Targets* and *System Constraints*. *Service Targets* consist of the *Delivery Ratio* and the *Delivery Delay*, while *System Constraints* refer to *Storage Space* and *Energy Availability*. We investigate tradeoffs between the above-mentioned sys-

tem properties and *conjecture* that high delivery ratio comes at the cost of high delivery delay and vice versa. Based on our conjecture, we propose a *design position* for DTN algorithms. Our position suggests that *high delivery ratio requires careful forwarding decisions*, while *low delivery delay requires greediness* (with regard to resource consumption). We argue that protocols for DTNs have to be designed on a *service target-driven fashion.*

3. We survey recent studies, covering the whole spectrum of protocol stacks intended for DTN, that we consider important. In Sections 4, 5, 6 and 7, we discuss architectural proposals as well as proposals for the application-, the transport- and the network-layer, respectively. A "paper map" can be found in Figure 2. We evaluate related studies and find that most of the times their design perspective follows (implicitly or explicitly) our design proposals.

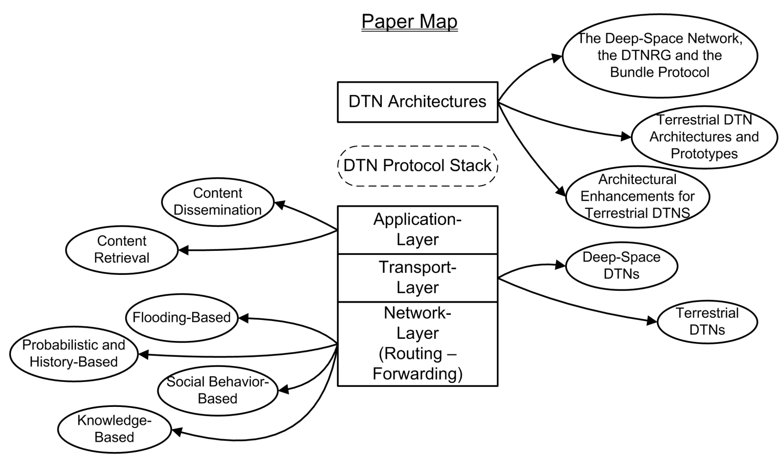

Figure 2: Paper Map

4. Finally, in Section 8, we discuss research challenges for Delay-/Disruption-Tolerant Networks. We attempt to deal with skepticism that has recently been brought up by a part of the research community and questions the usefulness of DTNs. In particular, some say that with the evolution of 3G networks, we have already entered the ubiquitous connectivity era and hence, there is no need for opportunistic networking research. We also

discuss issues related to *"killer apps"* for challenged networks.

To the best of our knowledge, this is the first study that attempts to examine the whole area of DTN and addresses open issues related to DTN research as a whole. Although studies such as [9], already provide a good background on specific aspects of DTNs, we believe that a more thorough look is needed before large-scale deployments take place.

2. Problem Statement

Clearly, there exists huge diversity among the several different application scenarios for DTNs. So, the challenging question that one may pose, is: *"Can one protocol stack deal with all potential DTN application scenarios?"*. For example, application diversity in the Internet is handled through the homogeneous common TCP/IP protocol stack and innovation is mainly pushed to the application layer. However, in the terrestrial Internet, continuous connectivity can be assumed in the majority of instances and delays are very small allowing for rapid responses and use of tight, closed control loops. In DTNs the situation is different: connectivity comprises the exception rather than the rule and control loops, like end-to-end connectivity and the path between source and destination, are not closed. Therefore, timeliness, in terms of data delivery deadlines, may be difficult to meet.

Moreover, it is not defined yet whether *100% reliability* (in terms of *delivery ratio*) is always required. For example, although reliable transmission is essential for applications such as telecommand, or e-mail, the case may be different for telemetry or road traffic management. If (non-critical) telemetry packets are collected on a one-second basis, for instance, then loss of one (or more) packets will probably not have major impact on the outcome of the monitoring application. In contrast, trying to provide full reliability to a telemetry application may negatively affect the system's performance as a whole. Imagine, for example, a sequence of telemetry packets being trapped in a portion of a DTN. This information will keep on consuming valuable network resources (i.e., storage space) and in turn, the node will not be able to serve new nodes/applications, due to storage space shortage. We attempt to place some of the foreseable DTN applications in the *Delivery Ratio - Delivery Delay Design Space* in Figure 3.

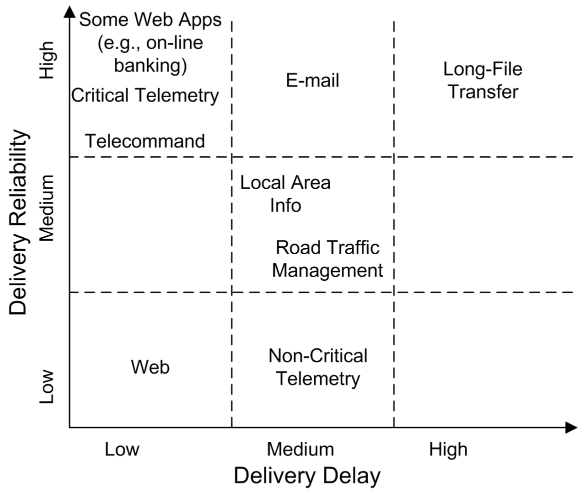

Figure 3: Delivery Reliability - Delivery Delay Design Space for DTN Applications

Since the DTN ”killer app” is yet to be found [8], we pick some well-known, but still DTN-applicable applications in order to illustrate the required service differentiation. Email requires 100% *delivery reliability*, but is not strict in terms of *delivery delay*. In contrast, ”web-on-the-move” or non-critical telemetry data becomes useless if not delivered within (relatively) strict deadlines.

Applying similar policies to the above applications may drain the system's energy in case of e-mail flooding, or saturate the system's storage in case of reliable delivery of non-critical telemetry, for instance. We argue that holistic, ”one-fits-all” approaches for DTN protocols will lead to deadlocks similar to the ones that the research community faces presently in the conventional Internet (e.g., mice vs elephants). In contrast, *proactive, service-target driven* designs have the potential to provide supply according to demand, instead of reactive patches that would regulate demand according to supply.

3. Solution Framework

We consider there exist two ultimate goals a DTN system should attempt to achieve: (i) *(High) Delivery Ratio*, D_R, (ii) *(Low) Delivery Delay*, D_D. We call these two goals the *Service Targets* of a DTN system. Given that DTNs consist mainly of mobile, battery-powered devices, they will be constrained with regard to: (i) *Energy Consumption*, E and (ii) *Storage Space*, S. We refer to these constraints as *System Constraints* (Figure 4).

Although the vast majority of studies on DTNs refer to reliability (in terms of delivery ratio) and latency (in terms of delivery delay), they use these terms to *evaluate* the performance of their proposed algorithm. In other words, reliability and delivery delay are used as metrics. The novelty introduced here is that reliability and delivery delay are considered as *targets*, rather than *evaluation metrics* [10]. Therefore, they should proactively drive the design of DTN protocols, instead of reactively measuring the protocol's efficiency.

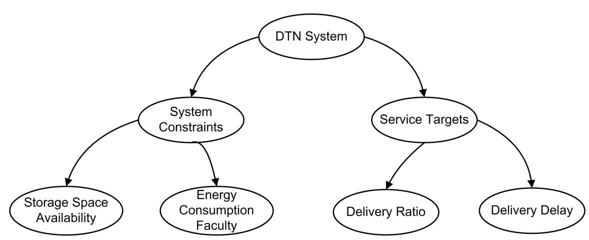

Figure 4: A DTN System, its *Service Targets* and its *System Constraints*

In [10], we discussed and analyzed observations from the related literature on DTNs. Through a number of conceptual steps and *consensus* statements, we *conjectured* that ***"it is either not possible, or at least very difficult for a DTN system to achieve both high Delivery Ratio and low Delivery Delay, given that the system is energy and storage constrained"***. Based on that, we proposed *Service Target Driven* protocol engineering/design. Our proposal is based on two *Design Position Statements.* We include our design position statements below and we refer the reader to [10] for further details.

3.1. Design Position

Conventional Internet applications usually require both high delivery ratio (reliability) and low delivery delay, since this is indeed possible. However, in the context of DTNs, given the above-mentioned *System Constraints*, we may have to trade one of the *Service Targets* in favor of operational viability. Our *Design Proposal* can be roughly summarized in the following *Position* statements:

POSITION 1. **To achieve high delivery ratio one has to make *wise* decisions.** *Wise decisions*, here, refer mostly to conservation of system resources, in particular, *energy* and *storage*. While storage is a *renewable* resource at run-time (i.e., once acknowledged messages are discarded, storage space becomes available again), the same is not true for energy, where once availability declines, the device is either "dead", or needs re-charging. Hence, we contend that to increase delivery probabilities, one has to be energy-efficient, or in other words *reduce transmissions to the minimum possible, even if this comes at the cost of delivery delay.*

POSITION 2. **To achieve low delivery delay one has to accept a degree of *risk*.** *Risky* forwarding decisions may be the ones for which we cannot predict that the probability of reaching the destination is high. However, to find the fastest possible path, one has to distribute copies to a *relatively large number of nodes*, with the hope that at least one of them will meet the destination within the deadline.

3.2. Discussion

Based on the above, we argue that algorithm design for DTNs has to be based on the desired performance outcome (i.e., the *Service Target*). That is, even if traditional DTN metrics, such as delivery delay, show good performance, the outcome has to be evaluated jointly with the corresponding application running on top. Differently put, if a system/node consumes all its energy to transfer e-mail messages as fast as possible, then this should be considered more of a waste, rather than a success, since the system/node will soon be useless, literally, for no reason. The interested reader can find an exercise scenario that illustrates the above arguments, in [10].

To the best of our knowledge, this is the first study that evaluates and criticizes the related literature on the basis of the *desired performance outcome*, rather than based on the performance of the corresponding algorithm only. Although there exist a number of interesting studies, such as [11], that elaborate on the performance tradeoffs for Delay-Tolerant Networks, none of them provides a system-wide categorization of the performance outcome taking also into account system constraints. For example, authors in [11] study analytically the tradeoff between delivery delay and resource consumption in challenged environments. Although their approach is interesting indeed and their analytical model seems promising, that study has some weak points. For example, the authors do not consider delivery reliability issues: how will the proposed model account for high delivery ratio? Moreover, the authors make a rather un-realistic assumption. In particular, they assume that once a packet is successfully delivered to its destination, all participating nodes are somehow informed about this fact and erase the packet in question from their memory. Clearly, some sort of algorithm/technique is needed in order to inform the rest of the nodes about the packet delivery. Otherwise, the nodes will inevitably run out of memory space in the long run.

Throughout the rest of the paper, we discuss recent studies related to Delay-Tolerant Networks. We follow a top-down approach protocol stack-wise and divide the related literature to: (i) Architectural or implementation proposals and the corresponding Prototypes (Section 4), (ii) Application-layer protocols for DTNs (Section 5), (iii) Transport-layer networking (Section 6) and (iv) routing/forwarding and network-layer issues (Section 7).

Whenever possible, we evaluate the research proposals with regard to our *conjecture*, presented in Section 3. In particular, we attempt to judge whether our *conjecture* is in line with the DTN research trends presently. We find that, in most cases, researchers tend to conclude that *increased delivery ratio comes at the cost of delivery delay and vise versa.* This result verifies the validity of our *Design Position Statements*, presented in Section 3.1.

4. DTN Architectures

In this Section, we discuss architectural issues that relate to DTN research. We initiate our discussion on DTN Architectures from the InterPlaNetary Internet and the official IETF documents, namely RFC 4838 [12] and its supporting Bundle Protocol Specification, RFC 5050 [13], produced by the IRTF [7] DTN Research Group (DTNRG [1]). Next, in Section 4.2, we present prototype implementations that target terrestrial challenged environments and finally, in Section 4.3, we discuss architectural enhancements for terrestrial DTNs.

4.1. The Deep-Space Network, the DTNRG and the Bundle Protocol

The *Delay-Tolerant Networking Architecture* was initially proposed as an approach to make the InterPlaNetary Internet [2] a viable networking environment. Researchers focused on interconnecting different Planetary Internets. The goal was to implement a universal *network of networks*. As such, most effort was put on interconnection and interoperability issues, the definition the Bundle layer itself and its forwarding capabilities with regard to custody transfers, naming and addressing schemes and store-and-forward capabilities of intermediate nodes. In an early study [14], the author addresses important issues relating to the design of network protocols for challenged environments, in general and proposes that the DTN architecture should form an overlay that will embrace all potential challenged environments. The paper proposes a DTN architecture, which in many cases has formed the basis for later official documents, such as RFC 5050 [13]. However, most of the issues addressed in [14] still remain untouched from the IRTF DTN Research Group [1]. For instance, issues such as *routing and storage congestion* have not received much attention until now, the reason being that for deep-space missions connectivity times and routing paths are known in advance, and the overall network is very sparse, with stub links and few relay nodes.

In contrast, security and transport layer issues have been investigated by the DTNRG, but mostly on the direction of space communications [15], [16], [17], [18], [19], [20], [21], [22]. We argue that DTNRG has focused mainly on the InterPlaNetary DTN environment, leaving the rest of the DTN research activity untouched. That said, the Bundle Architecture and its supporting protocols, based on the fact that some network conditions are known ahead of time on the deep-space networking environment, focus mainly on increased Data Delivery Ratio (with the exception of PROPHET [23], which is the only routing proposal within DTNRG). We argue that this may not always be the case, especially when referring to terrestrial DTN deployments, where fast data delivery may be of more importance (e.g., vehicular DTNs [24]). Although there have been some efforts to make the Bundle protocol specification more flexible (e.g., the Delay-Tolerant Networking Retransmission Block [25], or the Delay Tolerant Networking TCP Convergence Layer Protocol [26]), routing or transport layer issues for terrestrial DTNs have not received any attention from the IRTF DTNRG so far.

Recently, authors in [27] reviewed the efforts and approaches of the IRTF DTNRG. The authors refer to issues such as naming, addressing and binding, fragmentation and error detection of DTN Bundles, custody transfers and congestion management and security considerations for DTNs. They report that the initial architecture that targeted mainly the deep-space communication environment, would poorly fit into terrestrial DTNs due to lack of design flexibility. They conclude [27], among others, that although lately there are some efforts such as the flexible "responsible entities" or custodians, the *late binding* and the *proactive/reactive fragmentation option*, there are still some important issues that need to be further investigated. These issues include routing, security and congestion management and control. In our opinion, to address such issues, some strict requirements that have been taken for granted (for the Deep-Space networking environment) may have to be relaxed. For example, full reliability may not always be a prerequisite. Or, knowledge of the system's properties with regard to connectivity times, for instance, may be absent.

In [28], the authors identify problems related with the specification of the Bundle Protocol and the corresponding architecture built on top. For example, they contend that absence of error detection mechanisms from the specification (e.g., checksums) prevents reliability in its *custody transfer* function [28]. In particular, a corrupted message may reach the destination successfully, but the node will only realize this fact once data is forwarded to the application running on top. In general, this paper points to interesting aspects of the Bundle Protocol and provides good direction for future work.

Summarizing, we agree with the authors in [28] that the Bundle protocol specification is more of a complex file format specification, rather than an internetworking protocol. Although this may have been done on purpose by the DTNRG, in order to allow for implementation- and/or application-specific settings, we contend that this way, the Bundle protocol becomes pretty complex and inflexible to fit to the whole spectrum of potential DTN deployments.

Architecture	IPN [2]	ZebraNet [29]	DakNet [30]	DieselNet [31] DriveThru [32]	Haggle [33]
Purpose	Space Exploration	Wildlife Tracking (Biological Interest)	Connectivity to Developing Countries	Vehicular DTNs Road Comms	Social and Pocket-Switched Networks

Table 1: DTN Architectures

4.2. Terrestrial DTN Architectures and Prototypes

Although Delay-Tolerant Networking is relatively new as an independent research field, there have already been a number of prototype implementations that target real evaluation of protocols designed for terrestrial DTNs (e.g., DakNet [30], ZebraNet [29], UMassDieselNet [31], [34]). We present the most important ones below (see also Table 1.

4.2.1. Wildlife Tracking - ZebraNet

In the ZebraNet project [29], researchers "equipped" Zebras in Kenya with sensor-enhanced collars in order to gather information regarding the animals' moving and social behaviors. The research team, which consists of both biologists and computer scientists, has taken into account high level of detail with regard to the setup and the implementation of the prototype. Their observations are reported in [29]. There, the authors test two different kinds of routing protocols, namely a flooding-based (see Section 7.1) and a history-based (see Section 7.2), which we discuss later on. They report interesting tradeoffs, with regard to energy-efficiency, storage requirements and delivery success.

4.2.2. Providing Connectivity to Developing Countries

Recently, a considerable amount of research has been carried out with the goal of *providing connectivity in developing countries.* As a representative, we refer to the *DakNet* project [30], which provides connectivity to remote villages in India and Cambodia. The main idea is the following: Computer-equipped kiosks within remote villages serve villagers with digital applications, requests for national documents, bank services, e-mail etc. Once the villagers' applications are gathered, they are transferred to the closest city, where Internet connection exists, with means of *mechanical backhauls* [34], such as public transport vehicles (i.e., buses) equipped with Wi-Fi devices. Obviously, the key challenge to such projects is keeping both implementation and running costs as low as possible.

On that direction, authors in [34] provide a thorough analysis of the setup: *Low-cost Communication for Rural Internet Kiosks Using Mechanical Backhaul.* As a reference point, they consider the Delay-Tolerant Network architecture, which was initially proposed in RFC 4838 [12] and later became the Bundle Protocol Specification [13] after Fall's detailed investigation in [14]. The authors discuss issues from the whole protocol setup (i.e., naming, addressing, location management, routing, mobility, security and application support) and conclude (though not with simulation results) that 100% reliable data transport and *intelligent* routing are pretty tricky issues, not easy to be dealt with. Conclusions in [34] are inline with our solution framework presented in [10] and the design statements presented earlier on in Section 3.1.

4.2.3. Vehicular Communications

Vehicular communications have attracted a lot of attention in recent years, based on early studies such as [35], [36], [37], [38], [39]. The ultimate goal of that field of research is to provide (some sort of) connectivity to commuters. However, due to different kinds of transportation vehicles, connectivity patterns differ a lot. For example, once operators find it profitable, communication infrastructure can be deployed in trains and provide not only connectivity, but also QoS guarantees [40]. On the other hand, route-free vehicles (such as buses [31], [24], planes [37] or private cars [41], [36], [32] and bikes [42]) have to tolerate long delays and intermittent connectivity. Therefore, the DTN technology is expected to apply to those environments as well.

4.2.4. Pocket-Switched and Mobile Social Networks

Social Networking sites, such as Facebook [43], LinkedIn [44], Twitter [45] and many others are expected to go mobile [46], [47]. That is, users will be able to exchange messages of common interest (e.g., friends' updates, upcoming events, news [48], [49]) on-the-fly (i.e., one-hop communication), without the need for Internet connectivity. In particular, it is expected that upon encounters, the mobile devices will query each other for *updated* content of common interest and exchange messages accordingly, without the need to connect to the Internet in order to get these updates. There are several challenges with regard to these kinds of networks. For example, with what frequency do devices exchange messages? Or, does one device search for messages with all its encounters? Every how often do devices connect to the Internet to update their content and in which cases is this needed? There are already a number of projects that investigate the above issues, e.g., the Haggle Project [50], the Million People Project [51], the SocialNets [52] and the PeerSoN project [53]. We discuss the routing implications of this kind of communication in Section 7.3.

In the Haggle project [50], [33], researchers attempt to establish a *people-centric approach to DTNs.* They investigate tradeoffs of reliability and data delivery delay in *Pocket-Switched Networks* [54], [55] and *Haggle applications.*

They gather potential *Haggle-user* preferences to realize delay and reliability constraints and built the *Haggle prototype.* The prototype includes also a variety of *Haggle Applications* that are expected to help in the establishment of routing and data dissemination algorithms. In the context of Haggle, these algorithms are designed according to users' service requirements (or the application's service targets) and the system's constraints. That said, we consider the Haggle's approach to be one of the most interesting approaches to DTN research, since it takes into consideration the application's and the user's preferences.

4.3. Architectural Enhancements for Terrestrial DTNs

Limited connectivity in terrestrial Delay-Tolerant Networks is directly interpreted into limited network capacity. That given, researchers have investigated ways to increase the available network capacity by increasing connectivity opportunities. Three main ways have been identified (see Table 2): (i) add extra infrastructure elements (e.g., [56], [57]), (ii) exploit alternative communication technologies to transmit data (e.g., [58], [59]) and (iii) exploit node mobility (e.g., [60]). We discuss each of the three different approaches in further detail below.

Architectural Enhancements	Adding Extra Infrastructure Elements	Exploiting Non-Random Mobility	Using Alternative Communication Technologies
Proposal	Throwboxes [56] Robots [62] [63] Message-Ferries [57] Data MULES [65]	Message-Ferries [57] [61] Node-Recruitment [60]	ParaNets [58] Infostations [64] Second Bluetooth [59] Short- and long-range Radios [66]

Table 2: DTN Architectural Enhancements

4.3.1. Increasing Capacity by Adding Extra Infrastructure Elements

In an early study, [65], authors investigate energy, storage and reliability tradeoffs in the context of *Data MULES* (Mobile Ubiquitous LAN Extensions). The idea is that MULE nodes move around a sensor network to gather sensing data and trigger buffer release on the corresponding (visited) nodes. The authors derive a technically sound model to estimate the performance of a sparse sensor network system [65]. Next, they verify their analytical results with simulations. Although the authors make several simplifying assumptions such as that MULEs do not exchange data in-between them, but only with (static) sensor nodes, their model can be easily extended to embrace various DTN environments. Among others, the authors report that high reliability (measured as Data Success Rate in [65]) comes at the cost of high storage requirement, which is in-line with Position Statement 1, presented earlier in Section 3.1. The above studies borrow ideas from similar approaches on the placement of sensor nodes within a field (e.g., [67], [68]).

Authors in [56] propose the use of *"throwboxes"* in order to increase the capacity of the network. Throwboxes are battery-powered devices with storage and processing capabilities, which once placed in strategic points within the network can increase the capacity of the network and therefore, improve the throughput of the system. The authors in [56] focus mainly on improving the reliability and energy-efficiency [69] properties of the system, rather than reducing the data delivery delay. Towards a similar direction, authors in [70] propose interfacing any highly partitioned ad-hoc network with the *range extension network*. In particular each isolated ad-hoc network can relay data from itself throughout "Cross-Layer Communication Agents" (CCAs) to the rest of the Internet and vice versa. The CCAs may sit on airplanes, low-earth orbit satellites, passing-by vehicles etc. Based on a cost function the authors identify the optimal trajectories of CCAs and evaluate the performance of the proposed architecture with regard to delivery delay, percentage of packets delivered successfully and throughput achieved per CCA. However, the authors do not elaborate on performance tradeoffs among the above-mentioned system properties themselves.

In [62] and [63] the authors propose adding autonomous agents into the system, called robots, in order to increase transmission opportunities. They also study and influence, whenever possible, the movement of the system's participants (i.e., DTN nodes). Although it is questionable whether this approach will increase or decrease the energy efficiency of the system as a whole, deployment of robots may indeed be useful in some DTN environments from a *reliability* or a *delivery delay* perspective. In essence, works such as [56] and [62] depart, in our opinion, from the *message-ferrying* approach proposed originally in [57], or a similar earlier approach presented in [60]. We elaborate on these studies in Section 4.3.2.

4.3.2. Increasing Capacity by Exploiting Non-Random Node-Mobility

There has been a considerable amount of research originally triggered by theoretical studies on the capacity of wireless networks, such as [71], [72], [73]. In [71], the authors prove that *"Mobility increases the capacity of ad-hoc networks"*. In particular, they show that *when delay-constraints are not tight, network capacity and therefore, throughput as well, increases significantly.* However, improvement in throughput, which in turn means increased reliability, increases the data delivery delay (in-line with *Position 1*). Based on that, authors in [74] investigate data transport mechanisms in wearable computer environments. For example, humans equipped with wearable computers can carry information gathered when walking-by static nodes, who make request for a service (e.g. request for refill of a coffee machine within a train station). Authors in [74] investigate several approaches for packet drop strategies, acknowledgment or timeout-driven retransmissions and routing algorithms. They also investigate tradeoffs between reliability and energy-efficiency of battery-powered devices [74].

In [57], the authors propose deployment of special nodes, called *message ferries*, which exploit the nodes' *non-random* mobility patterns in order to collect messages and deliver them to their destination. The purpose is to reduce energy consumption and increase reliability (referred to as delivery delay performance in the original paper [57]) - see *Position 1.* The authors explore interesting tradeoffs, between *message delay, message delivery rate, buffer sizes* and *delivered messages per unit time.* In a later work, [61], the same authors, attempt to *control the mobility of multiple data transport ferries* in order to minimize the average data delivery delay. In [60], the authors propose *"recruiting"* nodes to transfer the data message from source to destination. In other words, the authors propose adjustment of the movement trajectory of nodes in order to suit the needs of the message's path/route. We expect that approaches such as [62], [57], [60] and [61] have limited applicability, since in essence, the nodes/users serve the communication system's needs, instead of the opposite.

4.3.3. Increasing Capacity Using Alternative Communication Technologies

In [58], the authors propose exploitation of all available network technologies (e.g. satellite networks, cell networks, etc.) in order to optimize the performance of Delay Tolerant Mobile Networks (DTMNs). According to the *Parallel Networks* (or *ParaNets* architecture [58]), the DTN application will have the opportunity to choose among a number of different transport-, network- and link-layer protocols in order to optimize the corresponding performance metric. Clearly, exploiting all the available means of transferring data, the capacity of the extended *Parallel Network* increases [71]. They show, for instance that *an application that sends ACK packets through the cellular network, instead of the satellite one, has the potential to release storage space much faster.*

In [66], the authors (based on their previous investigation on power management for delay-tolerant networks [75]) propose usage of two radios: a long-range, high power radio and a short-range, low-power one. The low-power, short-range radio is used by DTN-nodes in order to discover whether there are other nodes within range. Once they find that there are some neighbors around, the long-range radio is enabled in order to transmit/receive data. The authors explore energy-efficiency issues with regard to the interval between sleep and wake-up times; moreover, they explore tradeoffs between energy consumption and data delivery delay. In a similar study, [59], authors propose addition of a second Bluetooth radio in the numerous Bluetooth-enabled devices. Conclusions in [59] and [66] are generally inline with our design considerations included in [10].

Tradeoffs between different communication technologies have been investigated also in the context of *Infostations* [64]. Infostations can provide users/nodes with alternative means of transmitting data to/from the destination/source end-point. However, their performance is obscured by capacity-delay tradeoffs, which cannot be efficiently dealt with and mainly depend on the application in question. In [76], the authors extend the *Infostations* paradigm to a *Shared Wireless Infostation Model* (SWIM), where data is replicating and disseminating itself, in order to reach the Infostation faster. Again, however, capacity is compromised due to more dense data-/information-dissemination. The authors in [76] provide a thorough analysis of delay - capacity - storage tradeoffs. Authors in [77] extend the SWIM model and propose modifications for *improving storage by increasing complexity* and *improving energy by restricting transmissions*. Results and conclusions in both [76] and [77] are in accord with our design positions included in [10] and discussed in Section 3.

5. Application-Layer

The design of application layer protocols for delay-/disruption-tolerant networks may be the most challenging of all tasks. That is, while the architecture itself and the supporting network- and transport-layer protocols will need to deal and interoperate with system components, which are set, fixed and known (or can be communicated between nodes), the application has to deal with arbitrary parameters, namely, *the users' preferences* as well. The users' preferences consist, among others, of the user's think times, patience before response is received, typing and web-surfing habits. Of course, this requirement refers to applications dealing with users waiting for the system's response in front of the computer screen (or the mobile device, in general).

An interesting approach to new applications is made in the Haggle Project [50], where researchers are building a new architecture to enable *Pocket Switched Networking* [54]. In such environments, users can exploit both local and global connectivity. More precisely, the idea is to switch from the *node-centric* paradigm to the *data-centric* one. In that case, both a lot of new applications are immediately available and existing ones can perform better [33].

We note that the discussion included in this Section is only an initial attempt to identify the potential deployability of Internet applications to DTN environments. As already mentioned earlier, the killer application for DTNs is yet to be found [8]. Below, we discuss some of the most important research contributions to date with regard to the deployment and implementation of DTN-applications. Research efforts on that direction focus mainly on the changes and the modifications required in order to make *existing* Internet applications and their supporting protocols delay- and disruption-tolerant. In particular, researchers have focused on: *(i) Content Dissemination* and *(ii) Content Retrieval* (Table 3).

Application Issues	Future Applications (Mobile Social Nets)	Content Dissemination	Content Retrieval
Proposal	Pocket-Switched Networks [55] Haggle [33] Habit [49] Music Sharing [48]	ARTour Web Express [78] Disruption Tolerant Shell [80] DTN-Mail Gateway [82] CarNet [35] CarTel [83] Bundling the Web [84] HTTP-DTN [85] [86]	Data Retrieval Techniques [79] Content Storage and Retrieval [81] *Thedu* [24]

Table 3: DTN Application Design Issues

5.1. Content Dissemination

In [84], the authors propose *"Bundling the Web"*: currently, in order to download the contents of a web page, the host opens several sessions (i.e., TCP connections) each of which is responsible for some part of the content (e.g., text or figures). In [84], the authors propose that the contents of a web-page could be included in a single bundle (using MHTML [87], for instance), in order to avoid "chatty" transactions. Again, however, although the proposed architecture seems promising, issues related to performance tradeoffs are not addressed. For example, how would the user's patience and think times affect the design of the architecture and its supporting protocols?

In [85], the authors propose HTTP-DTN, a new version of HTTP/1.1. adjusted to the needs of challenged environments. In particular, the authors propose that once two nodes are in contact, HTTP should act as a peer-to-peer protocol (running over the appropriate convergence layer [88]) and allow *bidirectional* transmission of multiple files. This way, both nodes (either source/destination nodes, or simply relays) make the most out of each connectivity interval. In [88], the same authors specify the appropriate convergence layers for different transport protocols, while in [86] they attempt to decouple HTTP from TCP and enable its use with other more suitable transports (each time depending on the environment). The goal is to make *HTTP the waist in the hourglass of the DTN protocol stack*, similar to IP in the TCP/IP protocol stack.

In an earlier work, [78], the authors insert *Interceptors* (i.e., proxies) to accommodate HTTP traffic for intermittently connected environments. In particular, two proxies are used: the *Client Side Interceptor* and the *Server Side Interceptor*. The service, which is called "ARTour Web Express", enables *Asynchronous Request/Response Operation Mode* and *Disconnected Operation*. The main idea is that requests are buffered, if connectivity is absent, and are processed once communication resumes. Such an application can indeed be deployed in mobile environments, e.g., in transportation vehicles. However, scalability issues with regard to the desired delivery reliability levels have to be investigated for applications such as web browsing, which are expected to attract a lot of attention by commuters (e.g., [24]).

An initial step to deal with scalability issues for DTN applications is made in [35], where the authors propose localized applications such as collaborative road congestion monitoring, route planning, fleet tracking etc., and study application scalability issues when thousands of nodes make use of the application. Along the same lines, authors in [83] implement and deploy a *Distributed Mobile Sensor Computing System*. The system is called CarTel and is deployed on vehicular automotives. Potential applications that can be served by CarTel are environmental monitoring, civil infrastructure monitoring, automotive diagnostics, geo-imaging and data-muling. CarTel is a query-based programming interface, which provides an easy way to design applications for DTNs. In vehicle-based communication systems (e.g., CarTel [83] or CarNet [35]), the requirement for limited energy consumption may potentially be relaxed, since in the near future mobile devices may have the option to be powered by the vehicle's engine. In that case, however, additional design issues arise. For example, *"Can we have common applications and protocols for energy-limited and non-energy-limited environments?"*. Such issues call for further investigation.

E-mail is expected to receive a lot of attention as a DTN application [82], [89]. By definition, e-mail is a delay-tolerant application, since the sender of an e-mail does not expect immediate response (i.e., the receiver may check his mail-box after hours or days). The protocols that support e-mail applications in the Internet, however, are not designed for delay-tolerant networks (i.e., POP, IMAP, SMTP, which run over TCP). In [82], the authors use the Bundle Protocol and introduce some network entities, such as the *DTN-Mail Gateway*, in order to enable e-mail access and distribution in challenged environments. That is, the user can send/receive e-mails while being in a partitioned portion of the network, both to/from users within the network partition and to/from the rest of the Internet. We contend that scalability issues have to be extensively investigated, with regard to energy, storage space resources and delivery reliability, before deployment of DTN-email, since this application is expected to be widely and extensively used. Similar considerations apply for the application proposed in [90], where the authors build DTN applications for mobile phones. The main idea is that the operator's infrastructure can be effectively *bypassed* by using ad-hoc networking techniques in order to make direct communication between users feasible.

Authors in [80] develop a disruption-tolerant telecommand application, called *Disruption Tolerant Shell* (DTS). In particular, they modify the basic functions of the remote shell management tool in order to make it disruption-tolerant; furthermore, they add to this functionality with a reliable and efficient publish-subscribe mechanism, called StateSync. The system makes sure that the commands will be disseminated and executed by all nodes as long as they get connected and also, that the commands will be executed only once. The results of the command/script execution are reported back to the issuing station in order to ensure successful completion of the telecommand task.

5.2. Content Retrieval

In [79], the author discusses *"Application Protocol Design Considerations for a Mobile Internet"*. The author discusses several issues related to application protocol design, such as naming and addressing, security, the role of intermediaries, user interfaces etc. In the discussion it is assumed that data transmission is based on asynchronous message transfer, in order to deal with the unique characteristics of mobile and frequently-disconnected networks. One of the conclusions of the paper is that *DTN applications have to be designed in order to anticipate user requirements ahead of time, instead of continuously making new requests*. This, for example, may mean that the DTN web browser downloads to the local cache more than one results after a search in a web search engine; in turn, the user has more possibilities to find the desired information than in the case of downloading the first search result only. This way, as the author claims, connectivity opportunities are obviously exploited more efficiently [79]. It is clear, however, that there exist a number of performance tradeoffs. Indeed, downloading more than one search result will (i) increase possibilities of success, (ii) reduce the information delivery time, but it will also increase (i) energy consumption, (ii) storage space requirements and (iii) network resource usage (e.g., bandwidth). Such tradeoffs are not discussed, although this would in our opinion impact the system's performance.

In a similar study, [81], the authors discuss data storage and retrieval issues in challenged, intermittently connected and highly-partitioned networks. In particular, they propose modifications for application-layer protocols so that content can be stored within DTN nodes even after it has been successfully delivered to its destination (e.g., this could be useful for popular web-pages within public transport vehicles; an example could be a famous news portal downloaded into a busy train). Several buffering and storage issues are discussed in [81], while simulation results show that indeed caching provides performance benefits. The directions and the conclusions in [81] are in line with our proposed design considerations. We argue, however, that thorough investigation is needed before wide deployment of caching techniques takes place, since although useful, they may have destructive consequences. For example, reliability issues are not addressed in [81]. Instead, Time-To-Live (TTL) timers are applied in order to discard "old" content. We argue that for some applications, content should be discarded only when delivery is guaranteed (e.g., e-mail), which is not achieved by applying "blind", application-independent TTL timers.

On the same direction, authors in [24] propose *"Thedu"*, a technique which speeds up web search across DTNs. Thedu prioritizes search results and delivers back to the user pages that are much more likely to be useful, than using simple search techniques. More precisely, Thedu, [24], classifies queries to one of three types, namely, *homepage*, *content* and *service query.* According to that classification, it determines the number of search results that need to be returned back to the user. The authors deploy and test their proposed set of algorithms on DieselNet [31]; their results are indeed encouraging. They report that Thedu increases the system performance by 12% due to its classification technique. This is because without making use of Thedu irrelevant web-pages returned back to the user, waste valuable bandwidth resources. There are, however, some issues that are not addressed in [24]. For example, Thedu returns more data to the user than in a simple web search. This, inevitably, increases both the system's energy consumption and the storage space resources required by the DTN system. Furthermore, the authors assume that each query has a specific deadline for delivery (i.e., a timeout). According to our design position, this means that delivery reliability declines, since after the deadline the system will not deliver the data to the user. It is not discussed, however, whether there are retransmission attempts or not [24].

6. Transport-Layer

We discuss proposals for the transport layer separately in two main subsections: proposals for data transmission in the deep-space environment, or the InterPlaNetary Internet [91], in Section 6.1 and proposals for terrestrial DTNs, in Section 6.2 (see Table 4). The rationale behind our chosen structure is as follows: in the deep-space environment, even when connectivity exists, delays are huge. In contrast, in a terrestrial DTN setup once connectivity is in place, communication is "Internet-like", delay-wise. Inevitably, this impacts significantly the corresponding design rules and principles.

Operational Environment	Deep-Space Network	Terrestrial DTNs	
		Conection Management	Congestion Control
Proposal	TP-Planet [92]	PCMP [93]	Transport Issues [94]
	SCPS-TP [95]	DriveThru Transport [93]	Alternative Custodians [96]
	CFDP [97]	Transport Enhancements [98]	Storage Routing [99]
	LTP [16]		
	LTP-T [19]		
	Saratoga [20]		
	DTTP [100]		
	DS-TP [21] [22]		

Table 4: Transport-Layer Proposals for Challenged Environments

6.1. Proposals for Deep-Space DTNs

The Consultative Committee for Space Data Systems (CCSDS) [101] designed the Space Communications Protocol Standards - Transport Protocol (SCPS-TP) [95]. SCPS-TP adopts TCP's main functionalities and extends them in order to deal with some of the unique characteristics of deep-space links [102]. The protocol operates in one of two modes: (i) the Van Jacobson Congestion Control mode, which is based on TCP-Vegas [103] and (ii) the Open Loop Rate Control, which utilizes "corruption-experienced" signals from the receiver side and transmits assuming there is no congestion on the link. The Open

Loop Rate Control scheme makes use of Negative Acknowledgements (NAKs), instead of the usual ACKs used in the Van Jacobson mode. An experimental performance evaluation of SCPS-TP can be found in [104].

The same committee has also proposed a file-oriented delivery protocol, the CCSDS File Delivery Protocol (CFDP) [97], which mainly includes transport-layer functionalities. File transmission can be executed reliably (acknowledged mode) or unreliably (unacknowledged mode). CFDP includes four modes for sending Negative Acknowledgments (i.e., Deferred, Immediate, Prompted and Asynchronous) and uses positive Acknowledgments (ACKs) as well, to ensure the receipt of critical PDUs.

Authors in [16], [17] designed a file-transfer, point-to-point protocol that can be applied as a DTN convergence layer. The Licklider Transmission Protocol (LTP) [16] divides each data bundle into two parts: the *red part* that has to be reliably delivered to its destination and the *green part*, which can accept transmission errors (unreliable delivery). As an extension to LTP comes the Licklider Transmission Protocol - Transport (LTP-T) [19], which is designed to deal with multihop data transfers. LTP-T operates identically to LTP when the bundle transfer is errorless, while it splits the multi-hop end-to-end connection to hop-by-hop transfers in case of transmission errors. In [105], the authors compare the performance of LTP and LTP-T. They find that the higher the percentage of *red parts* within the data block, the higher the end-to-end delivery delay.

Saratoga [20] is a reliable, rate-based, UDP/IP file transfer protocol developed by Surrey Satellite Technology Ltd. [106]. Saratoga is capable of transferring large volumes of imaging data over dedicated point-to-point links. It transmits data on the line rate (which is setup and known *a priori*) and it assumes that coding techniques at the link layer deal with link errors. Saratoga also makes use of negative acknowledgments in order to guarantee full reliability. It can be used as a convergence layer to exchange DTN Bundles [20].

In [100], the authors design DTTP, a *Delay-Tolerant Transport Protocol*, in order to increase reliability and efficiency (in terms of resource utilization).

Clearly, the protocol targets deep-space communications and applies to both IP-enabled and non-IP protocol stacks. DTTP can provide both reliable and unreliable communication. The authors discuss tradeoffs between reliability and end-to-end delivery delay. That is, full reliability requires extensive retransmissions, which obviously extends overall transfer time.

In [21], [22], the authors propose DS-TP, the *Deep-Space Transport Protocol*. DS-TP inserts redundant packets into the deep-space link to proactively deal with increased bit error rates. It provides reliable communication exploiting a combined SACK - SNACK scheme. The level of redundancy introduced by DS-TP affects both the storage space requirement of intermediate DTN nodes and the end-to-end delivery delay of data to its destination. In contrast to related proposals, such as Saratoga [20] and LTP [16], which assume strong link-layer coding, DS-TP [21] deals with errors using redundant packet transmission. The techniques included in DS-TP are shown to improve the performance of the transport-layer protocol significantly [22]. Further investigation is needed to decide whether link-layer coding or transport-layer redundancy is preferable, or a sophisticated hybrid of the two.

6.2. Proposals for Terrestrial DTNs

Traditionally, there are two fundamental issues that a transport-layer protocol has to deal with: (i) management of the connection's state and (ii) congestion control. Both of these issues have to be reconsidered in the context of Delay- and Disruption-Tolerant Networks. Disruptions in connectivity would normally make the transport layer protocol abort the connection, while Internet congestion control rules mainly apply to the intermediate network entities (i.e., routers). In contrast, in DTNs a connection may need to be kept alive, despite connectivity disruptions, while control of congestion events at intermediate routers is reformed to *storage* congestion control of DTN-nodes, who run out of memory space (i.e., not necessarily buffer space only). We discuss each of the above challenges for transport-layer protocols below.

6.2.1. Connection Status

In disruption-prone environments, connection setup and tear-down is non-trivial, compared to the short-delay, always-connected Internet. On that direction, a number of studies have investigated disconnection-tolerant mechanisms for transport layer protocols. In [93], the authors introduce PCMP, the *Persistent Connection Management Protocol*, whose main functionality is to keep the TCP connection open during disconnections in Drive-Thru DTN enviroments [32]. Their approach is similar to "split-connection" transport layer protocols, such as Snoop-TCP [107], proposed in the past for TCP over wireless.

The authors in [93] discuss important aspects that need to be addressed with regard to data transfers within connectivity islands in Drive Thru environments. For example, the connectivity of a car that enters a "road WLAN" is split in three phases: (i) the *entry phase*, (ii) the *production phase* and (iii) the *exit phase*. If the data transfer is not completed within the production phase, then the state of the connection has to be kept alive till the car reaches the next connectivity island. In the same study, [93], the authors also experiment in a real road scenario and show that indeed, big amounts of data can be transferred even when the car's speed is high.

In a similar study, [98], the authors combine previously proposed techniques, namely the TCP User Timeout Option [108] and the TCP Retransmission Trigger [109] with the Host Identity Protocol [110]. The enhanced protocol can: (i) avoid connection aborts due to disconnection periods, utilizing the TCP User Timeout Option [108]; (ii) utilize more efficiently connectivity periods due to more efficient retransmission timeout settings (using the TCP Retransmission Trigger [109][2]) and (iii) avoid connection aborts due to IP address change, using HIP [110].

Although the above studies comprise a good starting point for the evaluation of "Drive-Thru" internets (or in general vehicular networks), there are

[2]Similar results and design approaches regarding the TCP-RTO have been previously reported in [111].

still many issues warranting further examination. For example, in [93] the next "connectivity island" for a car moving on a highway is assumed to be known in advance. This, however, will not be the case in real, wide-deployment scenarios (i.e., cars would normally move arbitrarily). Furthermore, issues of data volume, access point density and network contention (i.e., how many flows are currently within the same connectivity island) need to be addressed as well. On that direction, the transport-layer protocol's performance needs to be extensively investigated: available capacity has to be allocated rapidly, in order to utilize to the highest possible extend the connectivity period; bandwidth allocation issues may have to be reconsidered in case of DTN environments; noisy channels degrade TCP's performance further, something that has to be investigated together with energy consumption issues, which are not considered in the above studies. Last but not least, acknowledgment strategies that would trigger re-allocation of storage resources (in order to avoid storage congestion, for instance) have to be investigated in conjunction with reliability issues (i.e., discarding a message that has not yet been delivered to its destination would degrade system reliability). The research community will have to consider alternative transport layer schemes (such as for example [112], [113], [114], [115]) for efficient data transmission in challenged environments. Implementing conventional TCP, or TCP-like approaches in such environments would probably lead to poor performance.

6.2.2. Storage Congestion Control

Storage congestion control in DTN environments is heavily affected by the acknowledgment strategy of the transport-layer protocol. Once data is acknowledged, the corresponding messages can be discarded and storage space becomes available.

The main study that elaborates on acknowledgment strategies for DTN environments is [94]. The authors focus on the delivery ratio performance of different strategies and on the time that a message needs to be stored before it is ACKed and discarded. They use the following scenario: a message is forwarded from a source node S to a destination node U through a number of forwarding nodes F. They consider four different acknowledgment strategies and investigate end-to-end reliability issues with regard to end-to-end delays [94]. In particular, the acknowledgment strategies considered are:

1. *hop-by-hop*, where each F node accepts custody transfer and sends immediately an ACK back to the node whom it received the message from,
2. *active receipt*, where an ACK is generated from the U node once it receives the message; the ACK message flows back to the *infected* nodes in order to *cure* them,
3. *passive receipt*, where the U node generates a *kill message*, which is forwarded backwards to the direction of the S node, only when a node tries to forward again the same message, and
4. *network-bridged receipt*, where alternative technologies, such as a cellular network is used to acknowledge receipt of a message.

Based on the above strategies, the authors investigate important tradeoffs between delivery reliability, queuing time and delivery ratio. The conclusions included in [94] follow our design principles introduced in [10]. For example, *while the active receipt guarantees 100% end-to-end delivery reliability, it increases the queuing time and consequently the overall delivery delay* (*Position 1*). *Furthermore, the hop-by-hop strategy reduces the storage requirement and the end-to-end delivery delay, but it cannot guarantee end-to-end (i.e., 100%) delivery reliability* (*Position 2*). Obviously, the *network-bridged receipt* reduces both storage requirements and end-to-end delay, but one cannot guarantee that alternative means of transport (i.e., cellular networks) will always be available in a DTN setup.

Authors in [96] and [99] investigate *Storage Routing* approaches to avoid storage congestion in DTNs. The basic idea is that once a node becomes congested it forwards some fraction of its stored messages to *alternative custodians* in order to de-congest itself and therefore, be able to serve incoming traffic. The algorithm consists of two parts: the *message (to forward) selection* and the *node (to forward) selection.* The authors investigate push and pull operations with regard to *message completion rate*, *storage capacity* and *time weighted storage.* The tradeoffs discussed in [96] are largely consistent with our design framework. For example, *the authors conclude that high message completion rate (i.e., delivery reliability) requires huge storage capacity.* We argue, however, that although the analysis and the results presented in [96] and [99] are technically sound, energy issues are not taken into consideration. That is, circulating a node's stored content in order to serve incoming traffic may increase reliability, but it will also increase energy consumption. In turn, increased energy consumption will cause nodes to run out of battery; in the long-run, this will lead to reduced storage resources, system-wise, and consequently reduced potential for reliability guarantees. Furthermore, message circulation may potentially increase delivery delay, since data is not forwarded towards its ultimate destination node, but instead exchanged between neighbor nodes. Such issues clearly call for further investigation. Buffer management and dropping policies have also been investigated in [116], [117], [118].

7. Routing - Forwarding - Data Dissemination

Routing in Delay-/Disruption-Tolerant Networks is clearly the most difficult issue to deal with and clearly, the one that has attracted the most attention from the research community so far. In contrast to traditional networks where the routing protocol has to find the shortest path to the destination, a DTN-Routing protocol has to take more issues into consideration before making decisions. In particular, in conventional ad-hoc networks [4], [119] an end-to-end path is assumed to exist before data transmission is initiated. In contrast, in DTNs this rule does not hold. Therefore, routing protocols for DTNs have to deliver the message to the destination node using "store-carry-and-forward" techniques. There are three main approaches to DTN forwarding: (i) *Flooding/Epidemic or Replication-Based*, (ii) *Probabilistic or History-Based* and (iii) *Knowledge-Based.* The main issue with regard to DTN forwarding is *the number of copies* *that an algorithm should distribute into the network*. Here, we begin our discussion with some studies that provide insights on the design of DTN routing algorithms in general and then, we discuss each of the above three categories in turn. An older study with similar categorization can be found in [9].

In [120] the authors provide a *Formalism for Routing in Challenged Networks*. They classify challenged *Dynamic Networks* (DNs) into three main categories with regard to their increasing levels of connectivity. Specifically, they introduce *eventually connected* (ECDN), *eventually routable* (ERDN) and *eventually transportable* dynamic networks. Each routing mechanism is evaluated with regard to a number of attributes, such as *end-to-end path required* or not, *single-copy only* or not and *unavailable schedule* (i.e., knowledge) or not [120]. The authors attempt to assess the *solvability* of each routing mechanism. They reach important conclusions but do not take into consideration the delivery delay. That is, if a DN is *solvable*, given its attributes, then the message/bundle is delivered to its destination, regardless of the delivery timeframe. In a recent work, [121], the authors use graph theory and try to include delivery delay into the DTN-routing problem introduced in [120]. However, they relax the *unavailable schedule* attribute. In particular, they assume that contacts are predictable. A more complete routing framework using evolving graphs is presented in [122].

Routing Scheme	Flooding-Like Approaches		
	Flooding	Controlled Flooding	Flooding Under Resource Constraints
Proposal	Epidemic Routing [123]	Controlled Flooding Schemes [124] Spray-and-Wait [126]	Prioritized Epidemic Routing [125] Epidemic Under Contention [127] RAPID [128]

Table 5: Flooding-like Approaches for DTN Routing

7.1. Flooding or Replication-Based Routing

7.1.1. Epidemic Routing

The most simple approach to *Replication-Based Routing* is *Flooding* or *Epidemic Routing* [123]. The basic properties of this approach were initially studied in [123]. The main idea is that the source node distributes a copy of the message to all its neighbors and the neighbors do the same with their own neighbors (which do not already have a copy of the message). Clearly, the message spreads quickly throughout the network, which reduces the delivery delay. Moreover, since there are a lot of copies of the message within the network, epidemic routing is said to increase the overall delivery ratio as well. This is how epidemic routing is referred-to in the related literature. Here, we argue (as the authors do as well in the original study [123]) that performance evaluation of epidemic routing is not so trivial.

In particular, as the number of messages increases, epidemic routing does not scale well with both reliability guarantees and delivery timeframes, due to its high resource requirement (i.e., storage and energy availability). In [123], the authors explore performance tradeoffs with regard to the number of hops that a message is "allowed" to travel. That is, for example, they show that *a 3-hop count limit can still achieve 100% delivery ratio with a cost of 33% to delivery delay*. Similar results are obtained for the storage resources available to each node. *When storage places are much less than the number of in-flight messages at any given time (something that cannot be known in advance), then delivery ratio declines and delivery delay increases* [123].

7.1.2. Controlled Flooding

In [124], the authors propose *controlled flooding* in order to save resources, but still achieve acceptable delivery delay. They introduce a number of interesting metrics, such as the *willingness* of a node to accept incoming messages and forward them further, or the *Times-to-Send* value, which limits the number of times a source or forwarding node sends the message to newly-encountered neighbors. They also use well-known features, such as the *Time-to-Live* (i.e., the hop-count limit, also referred as K-hop forwarding) and the *Kill Time* (amount of time before forwarding is suspended). Although the setup in [124] is pretty simple and cannot really reflect real DTN deployments, the authors present interesting performance evaluation results. In particular, they compare different forwarding schemes, such as the *basic probabilistic*, the *time-to-live*, the *kill time* and the *passive cure* (a method to cure infected nodes and free storage resources). They show that *all four schemes reduce the resource consumption (in terms of the number of messages sent in the network), while at the same time the delay may indeed increase*, in accord to our *Conjecture* presented in Section 3, but always within affordable timeframes [124]. In [77], the authors attempt to limit redundant transmissions of epidemic routing and discard already delivered messages the fastest possible in order to make storage space available to alternative flows.

In [126], the authors propose an innovative algorithm to control flooding according to the desired performance goal. According to *Spray and Wait* [126], the source node *sprays* a number of copies to its neighbors and *waits* with the hope that one of the neighbor nodes will meet the destination. This kind of forwarding obviously reduces the overhead induced by flooding approaches, but as the authors show, it can be adjusted to meet specific deadlines as well. For example, lower delays can be achieved through shorter *wait* periods. However, although *Spray and Wait* takes into consideration some important issues, such as contention which is omitted in related studies, there are still some issues that are not discussed in [126]. For example, the delivery ratio is not included in the algorithm's solution framework. In addition, it is not discussed whether this algorithm could be deployed in a scenario where the *"DTN terrain"* is not fixed. A performance evaluation of Spray and Wait can be found in [129].

7.1.3. Controlled Flooding based on Analytical Models

A number of studies have investigated the performance of epidemic routing using Markovian models [130], [76], [131]. In [131], the authors investigate storage - delay tradeoffs and propose the deletion of obsolete information from the network, in order to reduce storage requirements without affecting the overall delay. The proposed schemes, however, increase computational complexity, which fact may, in the long term, have some impact on the energy availability of the mobile devices.

Based on the analysis in [130], where the authors introduce stochastic models to approximate the end-to-end message delivery delay, authors in [132] and [133] use Ordinary Differential Equations (ODEs) to derive closed-form formulas for the overall delay required as node density increases. The authors also investigate "recovery" schemes with regard to different buffer management approaches. They show that (i) the performance of different recovery schemes depends on the infection process and (ii) node buffer sizing to limit packet loss and increase delivery reliability needs to be considered in conjunction with appropriate management schemes.

7.1.4. Controlled Flooding under Resource Constraints

Some researchers have gone beyond epidemic routing and K-hop forwarding to investigate issues such as *Prioritized Epidemic Routing* [125], or *Epidemic Routing Under Contention* [127]. Although [125] and [127] include a number of assumptions, which would not fit to all DTN environments (such as fixed terrain, high node density), their findings are interesting. For example, in [125], *the authors report an increase in the message delivery ratio by a factor of 1.4 against simple epidemic routing and by a factor of 4 against AODV, when buffer and bandwidth resources decline.* There are, however, no results reported in [125] with regard to either delivery or overall delay.

In [127] and [134] the authors argue that contention *has* to be taken into consideration, in contrast to the vast majority of studies, which contend that the sparseness of DTN environments relaxes this requirement. In [127] the authors derive analytical expressions for the delay performance of epidemic routing taking into account (i) finite bandwidth between nodes, (ii) scheduling opportunities and limitations in the presence of interference between DTN-nodes and (iii) scheduling limitations in the presence of interference from third parties (i.e., non-DTN nodes).

In [128], the authors deal with DTN routing as a *resource allocation problem.* RAPID, the Resource Allocation Protocol for Intentional DTN routing is a replication-based protocol that considers both storage and bandwidth constraints. It makes use of a control plane to gather information regarding network resources and a utility function according to which it decides which packet to forward once contacts exist. The utility function is calculated taking into account one of three metrics: (i) minimize maximum delay, (ii) minimize average delay and (iii) increase the number of packets that reach their destination within a given deadline. RAPID is indeed an interesting approach to hybrid DTN routing, but it has to be extended and further evaluated before its applicability is evident. For example, *energy consumption* issues are not discussed in [128]. Furthermore, per-packet calculation of the utility function may lead to scalability problems in the long term.

Routing Scheme	History- and Encounter-Based	Probabilistic	Knowledge-Based	Social Behavior-Based
Proposal	PROPHET [23] [135] MaxProp [31] Single-Copy [142] Spray-and-Focus [146] Last-Seen-First [148] Most-Mobile-First [148] Most-Social-First [148]	$(p, q)-$routing [136] DFT-MSN [139] [140]	Oracle-Based [137] DTN-Multicast [141] DTN Link State Routing [143]	Bubble-Rap [138] Habit [49] CAR [144] [145] SimBet [147]

Table 6: History-, Encounter-, Probability-, Knowledge- and Social Behavior-Based Approaches for DTN Routing

7.2. Probabilistic and History-Based Forwarding

As an alternative to epidemic routing, researchers focused on *Probabilistic Routing* approaches (Table 6), in order to reduce resource consumption. On that direction, some approaches are based on history information (e.g., contact history [23], [149], [150]), or mobility pattern learning-based techniques (e.g., for vehicles such as buses), which have fixed routes for the most part [63], or passengers that follow similar routes on a daily basis [48], while some others do not require any information-gathering (in terms of history information) about the network conditions or the movement of DTN nodes (e.g., [136]). Moreover, some studies retain multiple copies of a message in the network (e.g., [23], [136], [146]), while others focus on *single-copy* routing (e.g., [136], [142], [151]).

7.2.1. History- and Encounter-based Forwarding

A representative study for history-based probabilistic routing protocols is [23], where the authors propose PROPHET, the Probabilistic ROuting Protocol using History of Encounters and Transivity [135]. The authors assume non-random mobility (i.e., a user that visited a place several times in the past is very much likely that it will visit the same place at some point again in the future), calculate the *delivery predictability* and forward packets accordingly. That is, a node forwards a packet to its encounter, only if this encounter's *delivery predictability* is higher. One of the conclusions of [23] is that *to increase delivery reliability, one has to deploy larger storage space in order to avoid packet drops, which in turn increases delivery delay* (in line with the *Conjecture* presented in [10]).

In a similar study, [31], the authors extend their previous work [152] and propose MaxProp, a routing protocol which bases its decisions on whether to transmit (if time runs short) or delete a message (if storage space availability declines) on the *path likelihood*. The *path likelihood* metric is based on historic information of the nodes' encounters. MaxProp targets Vehicle-Based DTNs and its performance is evaluated on the UMassDieselNet testbed [31]. In general, studies such as [23], [153], [31] show that using history information regarding the past encounters can significantly increase the system's performance. In an earlier study, [154], authors investigated the same approach, but for connected (ad-hoc) networks. We note, however, that this may not always be possible (i.e., knowledge properties), in which case alternative protocols have to be deployed. For example, in a vehicular, urban network, cars move arbitrarily and it is very unlikely that a car will pass-by the same point twice or three times within given, relatively strict, deadlines of some (tens of) minutes.

In a comprehensive study, [142], the authors study *single-copy* routing techniques for DTN environments. They consider a number of different (single-copy) routing mechanisms and derive both analytical expressions and simulation results regarding their delivery delay performance. They use a variety of utility functions and transitivity information to enhance the algorithms under consideration, as well as timers to enrich the inter-contact encounter times. Authors in [142] conclude that *a carefully* *designed single-copy routing algorithm can be competitive to multi-copy alternatives, but with less resource requirements.* Again, however, it is not yet clear whether such an analysis can be used to model a free-space delay-tolerant network (i.e., a network that spans across a huge area, such as the highways of a whole country, or an underwater sensor network, e.g., [155]), or if results in that case still hold (e.g., single-copy algorithms may perform poorly, delay-wise).

In [146], the same authors investigate *multiple-copy* routing techniques for DTNs. In essence, the authors extend their previous study [126] discussed above, where they proposed *Spray and Wait*. In [146], they combine their findings from the *single-copy* routing [142] with the *Spray and Wait* algorithm [126] and derive the *Spray and Focus* algorithm [146]. *Spray and Focus* consists of two phases: (i) the *Spray* phase, where a limited number of copies is distributed in the network, similarly to the *Spray and Wait* algorithm [126], and (ii) the *Focus* phase, where each relay node makes use of utility functions, investigated in the *single-copy-case* [142], as if it was the only copy in the network. Authors in [146] contend that *in the single copy case, as well as in the case of Spray and Wait, the message may never reach its destination, if the deployment terrain is not bounded or is huge in size. Therefore, the system may suffer both low reliability and large delays. In contrast, in the Spray and Focus scheme, reliability guarantees increase at the expense of energy resources, compared to the single copy case* [146].

In an interesting recent study, [148], the authors address the issue of heterogeneous node resources and mobility patterns. That is, the above studies always assume (implicitly or explicitly) that all nodes have the same amount of energy and storage and moreover that they "walk randomly", but always according to the same pattern/model. In contrast, authors in [148], use a utility function similar to the ones discussed above (i.e., density of encounter history with the destination node, [142], [146], [154]), but complement this utility function with aspects of "node classes" (e.g., pedestrian, vehicles, static nodes etc.), where energy and resource characteristics are similar among nodes of the same class, but vary significantly among nodes of different classes. These aspects are implemented in mechanisms such as *Last-Seen-First (LSF) Spraying*, *Most-Mobile-First (MMF) Spraying* and *Most-Social-First (MSF) Spraying* [148]. Also, evaluation of the algorithms is made in a setup, where each node belongs to a small "community" and spends most of its time within this community's terrain, but also occasionally moves to others[3]. We consider that the networking community should focus on modeling and evaluation of heterogeneous conditions among DTN nodes and we think that [148] provides a solid first step on that direction.

7.2.2. Probabilistic Forwarding

As a reference paper for the second group of studies (i.e., the probabilistic ones that do not utilize history information), we refer the reader to [136]. According to the proposed (p, q) scheme, when a relay node meets the source node it accepts a copy with probability q $(0 \leq q \leq 1)$, while when a relay node meets another potential relay node, the latter accepts a copy with probability p $(0 \leq p \leq 1)$. Obviously, the destination node accepts a copy with probability 1. The authors study four general schemes of (p, q)-routing, namely: (i) Direct Source-Destination Delivery $(p = q = 0)$ (e.g., [71]), (ii) Two-Hop Forwarding $(p = 0, q = 1)$ (e.g., [71], [132], [133], [130]), (iii) Probabilistic Forwarding $(0 < p = q < 1)$ (e.g., [133], [131]) and (iv) Conventional Epidemic Routing $(p = q = 1)$ (e.g., [123]) [136]. The authors derive analytical expressions for the delivery delay distribution of (p, q)-routing algorithms. Such analysis can be very helpful in order to set discard-timers (i.e., timers upon whose expiration messages are deleted from the node's memory). The authors investigate delay - energy and delay - storage tradeoffs for the aforementioned schemes. *They report that energy-wise the two-hop forwarding is the most efficient, while storage-wise either a scheme with small value for p, or conventional epidemic routing itself perform best* [136].

In [139] and [140], the authors investigate a *Delay-/Fault-Tolerant Mobile Sensor Network for Pervasive Information Gathering*. They study analytically the performance of the network under (i) direct transmission and (ii) flooding schemes. They identify tradeoffs between service targets, namely delivery delay/ratio and system constraints, namely storage and energy resources and propose a DFT-MSN delivery scheme. Their proposal consists of (i) a data delivery scheme, which, based on the *delivery probability*, forwards the message to the appropriate neighbor nodes and (ii) a queue management scheme, which decides on whether to transmit or drop a stored message, based on the *message's importance*. Our opinion is that the analysis included in [139] and [140] is sound and the setup is rather realistic. Some of the authors' conclu-

[3] Community-based topologies were originally introduced in [23].

sions are in accord with our design considerations. For example, the authors contend that *to reduce energy consumption, delivery delay has to be compromised.* However, there is no discussion as to whether delivery delay has to be traded for increased delivery reliability. Moreover, the authors state that pure flooding approaches reduce delivery delay. We argue that this cannot be the case for energy-constrained nodes (see our *Conjecture*, in Section 3, or a more detailed discussion in [10]).

7.3. Social Behavior-Based Forwarding

There exists a number of studies that investigate the impact of human mobility and their (potential) social relations on the design and performance of the appropriate routing algorithm [156], [55], [157], [158], [159], [138], [160], [161], [162], [163], [147], [48]. Research in this field is mainly triggered from early works, such as [71], where the authors assume that the gap between contacts is light-tailed. Authors in [156] analyze a large number of traces from diverse human-mobility environments and find that *the inter-contact time distribution is heavy-tailed.* This result implies that routing algorithms for mobile (DTN) environments have to be tested under different mobility models than the Random Way-Point. In [55], the authors investigate human mobility models in conference environments and find that some nodes are more "popular" than others. That said, contact history-based forwarding algorithms may be benefited from such information. Apparently, "popularity" will impact energy and storage resources. In a similar study [164], the authors investigate the *path explosion* phenomenon and explore its impact on the performance of the forwarding algorithm. *Path explosion* is the phenomenon according to which, once a path to the destination is formed, the number of subsequent paths grows rapidly. This has a direct impact on the performance of several routing proposals, such as epidemic [123], which appear to perform similarly. Although storage and energy issues are not investigated, results in [164] call for further investigation as for the availability of forwarding paths within a DTN setup.

In [144] and [145] the authors extend the operational properties of utility functions to also predict future attributes of potential message carriers; the new notion, which includes both the utility functions and its predictability extensions is the *context.* The evaluation of a node's *context* is made based on two main criteria, namely the *rate of change of connectivity of the host* (i.e., how possible it is that this node will move and meet other nodes) and the *energy level* (i.e., how long will the node stay "on", so that it will be able to interact with encounters). The analysis is based on the fact that *"mobile networks are social networks after all, since mobile devices are carried by individuals"* [145]. The authors report acceptable delivery ratios with relatively low delivery delays and small overheads.

There is a considerable amount of research going on presently with regard to mobile social networks. The main issue there is that messages should be forwarded to nodes that are interested in the specific content of the message (e.g., latest update on football news, [49], [48], [165]). That said, there is no ultimate destination for the message - the message keeps on spreading once it finds nodes interested in its content. We envision that in the future millions of messages that relate to several aspects of people's social life will start spreading among mobile phones/devices. However, given the energy constraints of such devices, we argue that careful design is needed before wide deployment. Otherwise, the users will be faced with the situation where phones/devices become useless because of battery depletion due to message exchanging, while users still need them to make phone-calls, for example.

7.4. Knowledge-Based Forwarding - Deterministic Routing

There are several studies that investigate routing issues in Delay-/Disruption-Tolerant Networks, where full or partial knowledge of either the network topology or the inter-contact times is assumed to be given in advance [137], [141], [143], [166]. In an early study, [137], the authors evaluate the performance of a number of routing algorithms with varying knowledge regarding the network dynamics. The model takes into account finite buffer sizes as well. The level of knowledge that each algorithm has is given in *Oracles* (hence, the general name for this category of algorithms, *oracle-based*). For example, knowledge of the moving trajectory and hence, the meeting times of DTN nodes constitutes one *Oracle*, while knowledge of the storage space availability of each node constitutes another. The simplest algorithm, which has no Oracle and hence zero knowledge is called *First Contact* (FC). Some algorithms, such as the *Earliest Delivery* (ED) have Oracles regarding the Contacts (times and durations of any node at any time), while the most sophisticated algorithm, *Linear Programming* has Oracles for Contacts, Queuing (storage availability at any node at any time) and Traffic (demand at present or in the future). As expected, the authors conclude that *the more knowledge/oracles an algorithm has the faster it can deliver messages to* *the desired destination node.* However, they report also that algorithms with limited knowledge can also perform quite efficiently.

In [141], the authors study *Multicasting in Delay-Tolerant Networks.* They investigate how knowledge of the network dynamics benefits the system's performance. In particular, topology information and group membership are taken into consideration. In accordance with the results in [137], authors in [141] conclude that *even with partial knowledge, multicast routing algorithms can perform efficiently in DTN environments.* Also, they report that *due to the nature of multicast applications, topology information is more important than group membership information for the performance of multicast routing algorithms.*

As noted before, some research activity focuses on providing connectivity for developing countries [30], [34]. In this context, authors in [143] adjust Link State Routing for the needs of DTN routing in connection-isolated villages in developing countries. In particular, the authors assume that the routing protocol in such environments can have some knowledge regarding the approximate contact times and contact durations, since the connectivity carrier to the Internet is a public transport vehicle (e.g., a bus [157], or some other means of transport [34]), whose timetable is (at least approximately) known in advance. In general, some knowledge may indeed be available in such scenarios, or in public transport vehicle scenarios [157], [40], but again, we argue that their routes may change unexpectedly, due to congestion or accidents, for example. Therefore, one cannot exclusively rely on such a carrier, unless 100% delivery reliability is not required. That said, *apart from node-density, and resource heterogeneity among nodes, application diversity has to be taken also into account when designing routing algorithms for DTN environments.*

8. Research Challenges

It has been already six years since Fall's seminal paper, which proposed a Delay-Tolerant Network Architecture [14]. Since then, the field of delay-/disruption-tolerant and opportunistic communications has attracted tremendous attention with hundreds of papers, several research projects and many conferences and workshops organized around this research area. Lately, there exists a lot of skepticism as for the deployability, the applicability or even the need for this kind of communication. For example, telecommunication vendors and operators have not (yet) found any sound business model, revenue-wise and therefore completely ignore this field of research. Others contend that with the evolution of 3G networks, we already have ubiquitous connectivity (at least at the developed parts of this planet).

We argue on four main points:

1. **Implementing and maintaining infrastructure is not always profitable for the telecommunication vendors.** There exist places where implementing and maintaining connectivity cannot guarantee continuous revenue for the operator. In such places, users' demand is not enough to guarantee *Return Of Investment* for the telecommunication vendor. As an example, we refer to highways, overground/underground trains, parks and isolated villages.
2. **Joining the mobile operator's scheme is not always cost-efficient for customers.** There exist (and there will always exist) parts of the population that will not be able to afford the operators' mobile Internet offers. The parts of the population that either choose at will, or do not have alternative connectivity option will inevitably rely on opportunistic connectivity (at least when mobile) to access the Internet. We note that even in the competitive telecommunication market, there are still millions of users on a pay-as-you-go mobile-phone scheme, although contract offers are quite attractive.
3. **Internet connectivity is not always needed.** Future applications will demand for faster and more energy-efficient communications. For example, social-networking applications or smart-home-applications will demand for "one-hop communication" messages, where transmission through the Internet will be neither cost- nor energy-efficient.
4. **Scalability of Internet access through 3G links is questionable.** Last but not least, we argue that scalability of Internet access through 3G links is questionable, if we consider the amount of data that needs to be uploaded/downloaded *and* the rapid increase in user-demand. That is, nowadays only a small percentage of people use Internet on the mobile-phone (mainly young generations), something that will not be true in the years/decades to come.

Recently, authors in [167] quest for the *killer app* for DTNs, which will boost research investigations and allow for wide-scale deployments. Although the current *killer app* for the Internet (i.e., the World Wide Web) came about a lot later than the Internet itself, the case was not the same for MANETs, where research is gradually fading out. Indeed, in case of MANETs only a few military applications found their way to real implementation and triggered further research.

On that direction, we argue that a *Taxonomization* of the DTN applicable scenarios is needed to unveil the potential of opportunistic networks. As discussed before, DTNs may range from the Deep-Space Network, to road-communications and further to isolated regions of the planet. It is not clear yet whether these different DTN deployments will need to communicate/interoperate with each other [168]. In turn, this raises further issues. For example, *what will a suitable DTN protocol stack look like? Is it going to be one stack, or diverse depending on the local requirements? Will it support carrying the Bundle Protocol?* Furthermore, it is possible that there will be more than one *killer apps*, whose potential is not clear due to the vague targets of DTN research presently [10]. That is, the killer app for the Deep-Space network may be a telecommand application, which is not at all useful for road communications. Instead, traffic management may be the killer app in that case. For a public-transport vehicle, where a lot of individuals are within range of each other, social-networking, or latest news broadcast may attract a lot of attention.

We contend that the appropriate categorization of different scenarios together with the potential applications for each scenario and the corresponding protocol design according to *Service Targets* and *System Constraints* (see Section 3 and [10]) are essential in order to guarantee wide deployment and further research on that field.

9. Conclusions

We have questioned whether it is possible to design one protocol stack for all the potential DTN deployments. We defined the *Service Targets* (i.e., *Delivery Ratio* and *Delivery Delay*) and the *System Constraints* (i.e., *Energy* and *Storage*) for a DTN system and conjectured that it is difficult, if possible at all, to achieve both High Delivery Ratio and Low Delivery Delay, given that devices are energy- and storage-constrained. We formulated a Design Position for DTN algorithms according to our conjecture. Based on that, we discussed the most recent research studies in the context of Delay-/Disruption-Tolerant Networking, following a top-down approach: from the architectural proposals and the prototype implementations, to the application-, the transport- and the network-layer. We conclude the following:

Given the huge diversity between different DTN architectures and the (potential) corresponding applications, reliability- and delay-wise, we argue that a solution framework has to be established by the research community to embrace and coordinate research efforts in a focused manner. Otherwise, the applications'/users' needs for delay-tolerant networking will be obscured by system constraints. This solution framework should tame the requirements of diverse DTN environments either in one common, but still tunable, protocol stack or in multiple (potentially) cross-compatible DTN implementations.

References

[1] DTNRG: (Delay-tolerant networking research group, http://www.dtnrg.org)

[2] IPN: (Interplanetary internet project, internet society special interest group, http://www.ipnsig.org)

[3] Corson, S., Macker, J.: Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations, RFC 2501 (1999)

[4] Akyildiz, I.F., Lee, W.Y., Chowdhury, K.R.: Crahns: Cognitive radio ad hoc networks. Ad Hoc Networks **7** (2009) 810 – 836

[5] Akyildiz, I., Wang, X.: A survey on wireless mesh networks. Communications Magazine, IEEE **43** (2005) S23–S30

[6] Akyildiz, I.F., Wang, X., Wang, W.: Wireless mesh networks: a survey. Computer Networks **47** (2005) 445 – 487

[7] IRTF: (Internet research task force, http://www.irtf.org/)

[8] Crowcroft, J., Yoneki, E., Hui, P., Henderson, T.: Promoting Tolerance for Delay Tolerant Network Research. SIGCOMM Comput. Commun. Rev. **38** (2008) 63–68

[9] Zhang, Z.: Routing in Intermittently Connected Mobile Ad Hoc Networks and Delay Tolerant Networks: Overview and Challenges. IEEE Communication Surveys and Tutorials **8** (1st Quarter 2006) 24–37

[10] Psaras, I., Wang, N., Tafazolli, R.: Six years since first DTN papers. Is there a clear target? In: 1st Extreme Workshop on Communication (ExtremeCom 2009), Laponia, Sweden. (2009)

[11] Neglia, G., Zhang, X.: Optimal delay-power tradeoff in sparse delay tolerant networks: a preliminary study. In: Proceedings of the 2006 SIGCOMM workshop on Challenged Networks (CHANTS '06), New York, NY, USA, (ACM) 237–244

[12] Cerf, V., et al.: Delay-Tolerant Networking Architecture, RFC 4838 (2007)

[13] Scott, K., Burleigh, S.: Bundle Protocol Specification, RFC 5050 (2007)

[14] Fall, K.: A Delay-Tolerant Network Architecture for Challenged Internets. In: Proceedings of SIGCOMM '03, New York, NY, USA, ACM (2003) 27–34

[15] Symington, S., et al.: Bundle Security Protocol Specification, Internet-Draft, draft-irtf-dtnrg-bundle-security-05 (2008)

[16] Ramadas, M., Burleigh, S., Farrell, S.: LTP: Licklider Transmission Protocol - Specification, RFC 5326 (2008)

[17] Ramadas, M., Burleigh, S., Farrell, S.: LTP: Licklider Transmission Protocol - Motivation, RFC 5325 (2008)

[18] Farrell, S., Ramadas, M., Burleigh, S.: LTP: Licklider Transmission Protocol - Security Extensions, RFC 5327 (2008)

[19] Farrell, S., Cahill, V.: Evaluating LTP-T: A DTN-Friendly Transport Protocol. In: Proceedings of the Third International Workshop on Satellite and Space Communications (IWSSC). (2007)

[20] Wood, L., et al.: Saratoga: A Scalable File Transfer Protocol, Internet-Draft, draft-wood-tsvwg-saratoga-02 (2008)

[21] Psaras, I., Papastergiou, G., Tsaoussidis, V., Peccia, N.: DS-TP: Deep-Space Transport Protocol. In: Proceedings of the IEEE Aerospace Conference 2008, Big Sky, Montana, USA. (2008)

[22] Papastergiou, G., Psaras, I., Tsaoussidis, V.: Deep-Space Transport Protocol: A Novel Transport Scheme for Space DTNs. Elsevier Computer Communications (COMCOM), Special Issue on Delay-/Disruption-Tolerant Networks, to appear (2009)

[23] Lindgren, A., Doria, A., Scheln, O.: Probabilistic Routing in Intermittently Connected Networks. In: SIGMOBILE Mobile Computing and Communication Review. (2004)

[24] Balasubramanian, A., Zhou, Y., Croft, W.B., Levine, B.N., Venkataramani, A.: Web search from a bus. In: Proceedings of the second ACM workshop on Challenged networks (CHANTS '07), New York, NY, USA, ACM (2007) 59–66

[25] Symington, S.: Delay-Tolerant Networking Retransmission Block, Internet Draft, draft-irtf-dtnrg-bundle-retrans-block-02 (2008)

[26] Demmer, M., Ott, J.: Delay Tolerant Networking TCP Convergence Layer Protocol, Internet-Draft, draft-irtf-dtnrg-tcp-clayer-02.txt (2008)

[27] Fall, K., Farrell, S.: DTN: An Architectural Retrospective. Selected Areas in Communications, IEEE Journal on **26** (2008) 828–836

[28] Wood, L., Eddy, W., Holliday, P.: A Bundle of Problems. In: IEEE Aerospace Conference. (2009) 1–17

[29] Juang, P., Oki, H., Wang, Y., Martonosi, M., Peh, L.S., Rubenstein, D.: Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet. SIGARCH Comput. Archit. News **30** (2002) 96–107

[30] Pentland, A.S., Fletcher, R., Hasson, A.: DakNet: Rethinking Connectivity in Developing Nations. Computer **37** (2004) 78–83

[31] Burgess, J., Gallagher, B., Jensen, D., Levine, B.N.: MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks. Proceedings of INFOCOM (2006) 1–11

[32] Ott, J., Kutscher, D.: Drive-thru Internet: IEEE 802.11b for "automobile" users. Proceedings of INFOCOM '04 (2004)

[33] Scott, J., Hui, P., Crowcroft, J., Diot, C.: Haggle: A Networking Architecture Designed Around Mobile Users. In: Proceedings of the Third Annual IFIP Conference on Wireless On-demand Network Systems and Services (WONS 2006), Invited paper, Les Menuires, France. (2006)

[34] Seth, A., Kroeker, D., Zaharia, M., Guo, S., Keshav, S.: Low-cost Communication for Rural Internet Kiosks Using Mechanical Backhaul. In: Proceedings of MobiCom, New York, NY, USA, ACM (2006) 334–345

[35] Morris, R., Jannotti, J., Kaashoek, F., Li, J., Decouto, D.: CarNet: a scalable ad hoc wireless network system. In: Proceedings of the 9th workshop on ACM SIGOPS European workshop, New York, NY, USA, ACM (2000) 61–65

[36] Singh, J.P., Bambos, N.: Wireless LAN performance under varied stress conditions in vehicular traffic scenarios. In: Proceedings 56th IEEE VTC 2002-Fall, Volume: 2, Page(s): 743 -747. (2002) 743–747

[37] Lin, K.D., Chang, J.F.: Communications and entertainment onboard a high-speed public transport system. IEEE Wireless Communications **9** (2002) 84–89

[38] Briesemeister, L., Hommel, G.: Role-based multicast in highly mobile but sparsely connected ad hoc networks. In: Proceedings of MobiHoc '00. (2000) 45–50

[39] Gavrilovich, C.D., J.: Broadband communication on the highways of tomorrow. IEEE Communications Magazine **39** (2001) 146–154

[40] Psaras, I., Mamatas, L., Mendes, P.: QoS Control in Next Generation IP Networks: An Experimental Analysis of Flow-based and SLS-based Mechanisms. In: Proceedings of the Workshop on Networking in Public Transport (WNEPT 2006), Waterloo, Canada. (2006)

[41] Chen, Z.D., Kung, H., Vlah, D.: Ad hoc relay wireless networks over moving vehicles on highways. In: Proceedings of MobiHoc '01, New York, NY, USA, ACM (2001) 247–250

[42] Esbjrnsson, M., Juhlin, O., stergren, M.: The Hocman prototype fast motor bikers and ad hoc networking. In: Proceedings of MUM '02, ACM Press (2002)

[43] Facebook: (http://www.facebook.com/)

[44] LinkedIn: (http://www.linkedin.com/)

[45] Twitter: (http://twitter.com/)

[46] Lugano, G.: Mobile social networking in theory and practice. First Monday **13** (2008)

[47] TechReview: (Technology Review, A New Language for Mobile Phones, http://www.technologyreview.com/communications/23330/)

[48] McNamara, L., Mascolo, C., Capra, L.: Media sharing based on colocation prediction in urban transport. In: Proceedings of MobiCom '08, New York, NY, USA, ACM (2008) 58–69

[49] Mashhadi, A.J., Mokhtar, S.B., Capra, L.: Habit: Leveraging Human Mobility and Social Network for Efficient Content Dissemination in DTNs. In: Proceedings of WoWMoM '09, Kos, Greece. (2009)

[50] Haggle: (http://www.haggleproject.org/)

[51] AMillionPeopleProject: (http://www.amillionpeople.net/)

[52] SocialNets: (http://www.social-nets.eu/)

[53] PeerSoN: (Privacy-Preserving P2P Social Networks, http://www.peerson.net/)

[54] Hui, P., Chaintreau, A., Gass, R., Scott, J., Crowcroft, J., Diot, C.: Pocket-Switched Networking: Challenges, Feasibility and Implementation Issues. In: Proceedings of the Second IFIP Workshop on Autonomic Communications 2005, Athens, Greece. (2005)

[55] Hui, P., Chaintreau, A., Scott, J., Gass, R., Crowcroft, J., Diot, C.: Pocket-Switched networks and human mobility in conference environments. In: Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-tolerant networking (WDTN '05), New York, NY, USA, ACM (2005) 244–251

[56] Zhao, W., Chen, Y., Ammar, M., Corner, M., Levine, B., Zegura, E.: Capacity Enhancement using Throwboxes in DTNs. In: IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS). (2006) 31–40

[57] Zhao, W., Ammar, M., Zegura, E.: A message ferrying approach for data delivery in sparse mobile ad hoc networks. In: Proceedings of MobiHoc '04, New York, NY, USA, ACM (2004) 187–198

[58] Harras, K., Wittie, M., Almeroth, K., Belding, E.: ParaNets: A Parallel Network Architecture for Challenged Networks. In: Proceedings of the IEEE Workshop on Mobile Computing Systems and Applications (HotMobile), Tucson, Arizona, USA. (2007)

[59] Liberatore, M., Levine, B.N., Barakat, C.: Maximizing transfer opportunities in bluetooth DTNs. In: Proceedings of CoNEXT '06, New York, NY, USA, ACM (2006) 1–11

[60] Li, Q., Rus, D.: Sending messages to mobile users in disconnected ad-hoc wireless networks. In: Proceedings of MobiCom '00, New York, NY, USA, ACM (2000) 44–55

[61] Zhao, W., Ammar, M., Zegura, E.: Controlling the mobility of multiple data transport ferries in a delay-tolerant network. Proceedings of INFOCOM 2005 **2** (2005) 1407–1418

[62] Burns, B., Brock, O., Levine, B.: Autonomous enhancement of disruption tolerant networks. Proceedings of IEEE International Conference on Robotics and Automation (ICRA) (2006) 2105–2110

[63] Burns, B., Brock, O., Levine, B.N.: MORA Routing and Capacity Building in Disruption-Tolerant Networks. Ad Hoc Networks **6** (2008) 600–620

[64] Goodman, D., Borras, J., Mandayam, N., Yates, R.: INFOSTATIONS: a new system model for data and messaging services. Proceedings of 47th IEEE Vehicular Technology Conference, 1997 **2** (1997) 969–973 vol.2

[65] Shah, R., Roy, S., Jain, S., Brunette, W.: Data MULEs: modeling a three-tier architecture for sparse sensor networks. Proceedings of the First IEEE International Workshop on Sensor Network Protocols and Applications (2003) 30–41

[66] Jun, H., Ammar, M.H., Corner, M.D., Zegura, E.W.: Hierarchical power management in disruption tolerant networks with traffic-aware optimization. In: Proceedings of the 2006 SIGCOMM workshop on Challenged networks (CHANTS '06), New York, NY, USA, ACM (2006) 245–252

[67] Cheng, X., Du, D.Z., Wang, L., Xu, B.: Relay sensor placement in wireless sensor networks. Wireless Networks **14** (2008) 347–355

[68] Pan, J., Hou, Y.T., Cai, L., Shi, Y., Shen, S.X.: Topology control for wireless sensor networks. In: Proceedings of MobiCom '03, New York, NY, USA, ACM (2003) 286–299

[69] Banerjee, N., Corner, M., Levine, B.: An Energy-Efficient Architecture for DTN Throwboxes. Proceedings of IEEE INFOCOM 2007 (2007) 776–784

[70] Ahmed, M., Krishnamurthy, S., Katz, R., Dao, S.: Trajectory control of mobile gateways for range extension in ad hoc networks. Computer Networks **39** (2002) 809 – 825

[71] Grossglauser, M., Tse, D.N.C.: Mobility increases the capacity of ad hoc wireless networks. IEEE/ACM Trans. Netw. **10** (2002) 477–486

[72] Perevalov, E., Blum, R.: Delay limited capacity of ad hoc networks: asymptotically optimal transmission and relaying strategy. In: Proceedings of IEEE Infocom. (2003)

[73] Bansal, N., Liu, Z.: Capacity, delay and mobility in wireless ad-hoc networks. Proceedings of IEEE INFOCOM 2003 **2** (2003) 1553–1563 vol.2

[74] Davis, J.A., Fagg, A.H., Levine, B.N.: Wearable Computers as Packet Transport Mechanisms in Highly-Partitioned Ad-Hoc Networks. In: Proceedings of the 5th IEEE International Symposium on Wearable Computers (ISWC '01), Washington, DC, USA, IEEE Computer Society (2001) 141

[75] Jun, H., Ammar, M., Zegura, E.: Power management in delay tolerant networks: a framework and knowledge-based mechanisms. In: Proceedings of Second International Conference on Sensor and Ad Hoc Communications and Networks (IEEE SECON 2005). (2005) 418–429

[76] Small, T., Haas, Z.J.: The shared wireless infostation model: a new ad hoc networking paradigm (or where there is a whale, there is a way). In: Proceedings of MobiHoc '03, New York, NY, USA, ACM (2003) 233–244

[77] Small, T., Haas, Z.J.: Resource and performance tradeoffs in delay-tolerant wireless networks. In: Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking (WDTN '05), New York, NY, USA, ACM (2005) 260–267

[78] Chang, H., Tait, C., Cohen, N., Shapiro, M., Mastrianni, S., Floyd, R., Housel, B., Lindquist, D.: Web browsing in a wireless environment: disconnected and asynchronous operation in ARTour Web Express. In: Proceedings of MobiCom '97, New York, NY, USA, ACM (1997) 260–269

[79] Ott, J.: Application protocol design considerations for a mobile internet. In: Proceedings of first ACM/IEEE international workshop on Mobility in the evolving internet architecture (MobiArch '06), New York, NY, USA, ACM (2006) 75–80

[80] Lukac, M., Girod, L., Estrin, D.: Disruption Tolerant Shell. In: Proceedings of the 2006 SIGCOMM workshop on Challenged networks (CHANTS '06), New York, NY, USA, ACM (2006) 189–196

[81] Ott, J., Pitkanen, M.J.: DTN-based Content Storage and Retrieval. In: Proceedings of the First IEEE WoWMoM Workshop on Autonomic and Opportunistic Communications (AOC). (2007)

[82] Hyyryläinen, T., Kärkkäinen, T., Luo, C., Jaspertas, V., Karvo, J., Ott, J.: Opportunistic Email Distribution and Access in Challenged Heterogeneous Environments. In: Proceedings of the second ACM workshop on Challenged networks (CHANTS '07), New York, NY, USA, ACM (2007) 97–100

[83] Hull, B., Bychkovsky, V., Zhang, Y., Chen, K., Goraczko, M., Miu, A., Shih, E., Balakrishnan, H., Madden, S.: CarTel: A Distributed Mobile Sensor Computing System. In: Proceedings of the 4th international conference on Embedded networked sensor systems (SenSys '06), New York, NY, USA, ACM (2006) 125–138

[84] Ott, J., Kutscher, D.: Bundling the Web: HTTP over DTN. In: Proceedings of the Workshop on Networking in Public Transport (WNEPT '06), in conjunction with QShine. (2006)

[85] Wood, L., Holliday, P.: Using HTTP for delivery in Delay-/Disruption-Tolerant Networks, Internet-Draft, draft-wood-dtnrg-http-dtn-delivery-03 (2009)

[86] Wood, L., Holliday, P., Floreani, D., Psaras, I.: Moving data in DTNs with HTTP and MIME; Making use of HTTP for delay- and disruption-tolerant networks with convergence layers. In: Proceedings of the first Workshop on the Emergence of Delay-/Disruption-Tolerant Networks (E-DTN '09). (2009)

[87] Palme, J., Hopman, A., Shelness, N.: MIME Encapsulation of Aggregate Documents, such as HTML (MHTML), RFC 2557 (1999)

[88] Wood, L.: Specifying transport mechanisms in Uniform Resource Identifiers, Internet-Draft, draft-wood-tae-specifying-uri-transports-06 (2009)

[89] Ott, J., Kutscher, D.: Why Seamless? Towards Exploiting WLAN-based Intermittent Connectivity on the Road. In: Proceedings of the TERENA Networking Conference (TNC). (2004)

[90] Mukhtar, O., Ott, J.: Backup and Bypass: Introducing DTN-based Ad-hoc Networking to Mobile Phones. In: Proceedings of the 2nd international workshop on Multi-hop ad hoc networks: from theory to reality (REALMAN '06), New York, NY, USA, ACM (2006) 107–109

[91] Akyildiz, I.F., Akan, O.B., Chen, C., Fang, J., Su, W.: InterPlaNetary Internet: State-of-the-art and Research Challenges. Computer Networks **43** (2003) 75–112

[92] Akan, O., Fang, J., Akyildiz, I.: TP-Planet: a reliable transport protocol for Interplanetary Internet. IEEE Journal on Selected Areas in Communications **22** (2004) 348–361

[93] Ott, J., Kutscher, D.: A Disconnection-Tolerant Transport for Drive-thru Internet Environments. Proceedings of IEEE INFOCOM 2005 **3** (2005) 1849–1862 vol. 3

[94] Harras, K.A., Almeroth, K.C.: Transport Layer Issues in Delay Tolerant Mobile Networks. In: Proceedings of IFIP Networking. (2006)

[95] SCPS-TP: (Space Communications Protocol Standards (SCPS). Transport Protocol (SCPS-TP) - Recommendation for Space Data System Standards, CCSDS 714.0-B-2. Blue Book. Issue 2. Washington, D.C., October 2006)

[96] Seligman, M., Fall, K., Mundur, P.: Alternative Custodians for Congestion Control in Delay Tolerant Networks. In: Proceedings of the 2006 SIGCOMM workshop on Challenged Networks (CHANTS '06), New York, NY, USA, ACM (2006) 229–236

[97] CFDP: (Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP)-Part 1: Introduction and Overview, CCSDS 720.1-G-3. Green Book. April 2007)

[98] Schütz, S., Eggert, L., Schmid, S., Brunner, M.: Protocol Enhancements for Intermittently Connected Hosts. SIGCOMM Comput. Commun. Rev. **35** (2005) 5–18

[99] Seligman, M., Fall, K., Mundur, P.: Storage Routing for DTN Congestion Control. Wirel. Commun. Mob. Comput. **7** (2007) 1183–1196

[100] Samaras, C.V., Tsaoussidis, V.: DTTP: A Delay-Tolerant Transport Protocol for Space Internetworks. In: Proceedings of 2nd ERCIM Workshop on eMobility, Tampere, Finland. (2008)

[101] CCSDS: (Consultative Committee for Space Data Systems, http://public.ccsds.org/default.aspx)

[102] Durst, R.C., Miller, G.J., Travis, E.J.: TCP Extensions for Space Communications. Wirel. Netw. **3** (1997) 389–403

[103] Brakmo, L.S., O'Malley, S.W., Peterson, L.L.: TCP Vegas: New Techniques for Congestion Detection and Avoidance. SIGCOMM Comput. Commun. Rev. **24** (1994) 24–35

[104] Wang, R., Aryasomayajula, N., Ayyagari, A., Zhang, Q.: An Experimental Performance Evaluation of SCPS-TP over Cislunar Communications Links. Proceedings of IEEE Wireless Communications and Networking Conference (WCNC '07) (2007) 2603–2607

[105] Muhammad, F., Franck, L., Farrell, S.: Transmission Protocols for Challenging Networks: LTP and LTP-T. In: Proceedings of the International Workshop on Satellite and Space Communications 2007 (IWSSC '07). (2007) 145–149

[106] SSTL: (Surrey satellite technology ltd., http://www.sstl.co.uk/)

[107] Balakrishnan, H., Seshan, S., Amir, E., Katz, R.H.: Improving TCP/IP Performance Over Wireless Networks. In: Proceedings of MobiCom '95, New York, NY, USA, ACM (1995) 2–11

[108] Eggert, L., Gont, F.: TCP User Timeout Option, Internet-Draft, draft-ietf-tcpm-tcp-uto-11 (2009)

[109] Eggert, L., Schuetz, S., Schmid, S.: TCP Extensions for Immediate Retransmissions, Internet-Draft, draft-eggert-tcpm-tcp-retransmit-now-02 (2005)

[110] Moskowitz, R., Nikander, P.: Host Identity Protocol (HIP) Architecture, RFC 4423 (2006)

[111] Psaras, I., Tsaoussidis, V.: Why TCP timers (still) don't work well. Computer Networks **51** (2007) 2033–2048

[112] Raghavan, B., Snoeren, A.C.: Decongestion Control. In: Proceedings of the 5th ACM Workshop on Hot Topics in Networks (HotNets-V). (2006)

[113] Dukkipati, N., McKeown, N.: Why Flow-Completion Time is the Right Metric for Congestion Control. SIGCOMM Comput. Commun. Rev. **36** (2006) 59–62

[114] Massoulié, L., Roberts, J.: Bandwidth Sharing: Objectives and Algorithms. IEEE/ACM Trans. Netw. **10** (2002) 320–328

[115] Bonald, T., Feuillet, M., Proutiere, A.: Is the "Law of the Jungle" Sustainable for the Internet? In: Proceedings of IEEE INFOCOM '09. (2009)

[116] Krifa, A., Barakat, C., Spyropoulos, T.: An optimal joint scheduling and drop policy for Delay Tolerant Networks. In: Proceedings of WoWMoM '08. International Symposium on a World of Wireless, Mobile and Multimedia Networks. (2008) 1–6

[117] Krifa, A., Baraka, C., Spyropoulos, T.: Optimal Buffer Management Policies for Delay Tolerant Networks. In: Proceedings of SECON '08, 5th IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks. (2008) 260–268

[118] Lindgren, A., Phanse, K.: Evaluation of Queuing Policies and Forwarding Strategies for Routing in Intermittently Connected Networks. In: Proceedings of Comsware '06. First International Conference on Communication System Software and Middleware. (2006) 1–10

[119] Akyildiz, I.F., Melodia, T., Chowdhury, K.R.: A Survey on Wireless Multimedia Sensor Networks. Comput. Netw. **51** (2007) 921–960

[120] Ramanathan, R., Basu, P., Krishnan, R.: Towards a Formalism for Routing in Challenged Networks. In: Proceedings of the second ACM workshop on Challenged networks (CHANTS '07), New York, NY, USA, ACM (2007) 3–10

[121] Shao, Y., Wu, J.: Understanding the tolerance of dynamic networks: A routing-oriented approach. In: Proceedings of the 2008 The 28th International Conference on Distributed Computing Systems Workshops (ICDCSW '08), Washington, DC, USA (2008) 180–185

[122] Borrel, V., Ammar, M.H., Zegura, E.W.: Understanding the Wireless and Mobile Network Space: a Routing-Centered Classification. In: CHANTS '07: Proceedings of the second ACM workshop on Challenged networks, New York, NY, USA, ACM (2007) 11–18

[123] Vahdat, A., Becker, D.: Epidemic Routing for Partially-Connected Ad Hoc Networks. Technical Report, Dept. of Computer Science, Duke University (2000)

[124] Harras, K.A., Almeroth, K.C., Belding-royer, E.M.: Delay Tolerant Mobile Networks (DTMNs): Controlled Flooding Schemes in Sparse Mobile Networks. In: Proceedings of IFIP Networking. (2005)

[125] Ramanathan, R., Hansen, R., Basu, P., Rosales-Hain, R., Krishnan, R.: Prioritized Epidemic Routing for Opportunistic Networks. In: Proceedings of the 1st international MobiSys workshop on Mobile opportunistic networking (MobiOpp '07), New York, NY, USA, ACM (2007) 62–66

[126] Spyropoulos, T., Psounis, K., Raghavendra, C.S.: Spray and Wait: An Efficient Routing Scheme for Intermittently Connected Mobile Networks. In: Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant Networking (WDTN '05), New York, NY, USA, ACM (2005) 252–259

[127] Jindal, A., Psounis, K.: Performance Analysis of Epidemic Routing Under Contention. In: Proceedings of the 2006 international conference on Wireless communications and mobile computing (IWCMC '06), New York, NY, USA, ACM (2006) 539–544

[128] Balasubramanian, A., Neil, B., Venkataramani, L.A.: DTN Routing as a Resource Allocation Problem. In: Proceedings of ACM SIGCOMM '07. (2007)

[129] Abdulla, M., Simon, R.: The Impact of the Mobility Model on Delay Tolerant Networking Performance Analysis. In: Proceedings of the 40th Annual Simulation Symposium (ANSS '07). (2007) 177–184

[130] Groenevelt, R., Nain, P., Koole, G.: The Message Delay in Mobile Ad Hoc Networks. Elsevier Performance Evaluation **62** (2005) 210–228

[131] Haas, Z.J., Small, T.: A New Networking Model for Biological Applications of Ad Hoc Sensor Networks. IEEE/ACM Transactions on Networking **14** (2006) 27–40

[132] Zhang, X., Neglia, G., Kurose, J., Towsley, D.: Performance Modeling of Epidemic Routing. In: IFIP Networking. (2006) 827–839

[133] Zhang, X., Neglia, G., Kurose, J., Towsley, D.: Performance Modeling of Epidemic Routing. Comput. Netw. **51** (2007) 2867–2891

[134] Ni, S.Y., Tseng, Y.C., Chen, Y.S., Sheu, J.P.: The Broadcast Storm Problem in a Mobile Ad Hoc Network. In: Proceedings of MobiCom '99, New York, NY, USA, ACM (1999) 151–162

[135] Lindgren, A., Doria, A.: Probabilistic Routing in Intermittently Connected Networks, Internet-Draft, draft-irtf-dtnrg-prophet-01 (2008)

[136] Matsuda, T., Takine, T.: (p, q)-Epidemic Routing for Sparsely Populated Mobile Ad Hoc Networks. Selected Areas in Communications, IEEE Journal on **26** (2008) 783–793

[137] Jain, S., Fall, K., Patra, R.: Routing in a Delay Tolerant Network. In: Proceedings of SIGCOMM '04, New York, NY, USA, ACM (2004) 145–158

[138] Hui, P., Crowcroft, J., Yoneki, E.: Bubble Rap: Social-based Forwarding in Delay-Tolerant Networks. In: Proceedings of MobiHoc '08, New York, NY, USA, ACM (2008) 241–250

[139] Wang, Y., Wu, H.: DFT-MSN: The Delay/Fault-Tolerant Mobile Sensor Network for Pervasive Information Gathering. In: IEEE INFOCOM '06. (2006)

[140] Wang, Y., Wu, H.: Delay/Fault-Tolerant Mobile Sensor Network (DFT-MSN): A New Paradigm for Pervasive Information Gathering. IEEE Transactions on Mobile Computing **6** (2007) 1021–1034

[141] Zhao, W., Ammar, M., Zegura, E.: Multicasting in delay tolerant networks: Semantic models and routing algorithms. In: Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking (WDTN '05), New York, NY, USA, ACM (2005) 268–275

[142] Spyropoulos, T., Psounis, K., Raghavendra, C.S.: Efficient Routing in Intermittently Connected Mobile Networks: the Single-Copy Case. IEEE/ACM Trans. Netw. **16** (2008) 63–76

[143] Demmer, M., Fall, K.: DTLSR: Delay Tolerant Routing for Developing Regions. In: Proceedings of the 2007 workshop on Networked systems for developing regions (NSDR '07), New York, NY, USA, ACM (2007) 1–6

[144] Musolesi, M., Hailes, S., Mascolo, C.: Adaptive Routing for Intermittently Connected Mobile Ad Hoc Networks. Proceedings of WoWMoM '05 (2005) 183–189

[145] Musolesi, M., Mascolo, C.: CAR: Context-Aware Adaptive Routing for Delay-Tolerant Mobile Networks. IEEE Transactions on Mobile Computing **8** (2009) 246–260

[146] Spyropoulos, T., Psounis, K., Raghavendra, C.S.: Efficient routing in intermittently connected mobile networks: the multiple-copy case. IEEE/ACM Trans. Netw. **16** (2008) 77–90

[147] Daly, E.M., Haahr, M.: Social network analysis for routing in disconnected delay-tolerant MANETs. In: Proceedings of MobiHoc '07, New York, NY, USA, ACM (2007) 32–40

[148] Spyropoulos, T., Turletti, T., Obraczka, K.: Routing in Delay Tolerant Networks Comprising Heterogeneous Node Populations. IEEE Transactions on Mobile Computing, to appear (2009)

[149] Jones, E.P.C., Li, L., Ward, P.A.S.: Practical Routing in Delay-Tolerant Networks. In: Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking (WDTN '05), New York, NY, USA, ACM (2005) 237–243

[150] Khelil, A., Jose Marron, P., Rothermel, K.: Contact-based mobility metrics for delay-tolerant ad hoc networking. In: Proceedings of MASCOTS '05: the 13th IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems, Washington, DC, USA, IEEE Computer Society (2005) 435–444

[151] Conan, V., Leguay, J., Friedman, T.: Fixed Point Opportunistic Routing in Delay Tolerant Networks. IEEE Journal on Selected Areas in Communications **26** (2008) 773–782

[152] Burns, B., Brock, O., Levine, B.: MV Routing and Capacity Building in Disruption Tolerant Networks. Proceedings of IEEE INFOCOM '05 **1** (2005) 398–408 vol. 1

[153] Leguay, J., Friedman, T., Conan, V.: DTN Routing in a Mobility Pattern Space. In: Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking (WDTN '05), New York, NY, USA, ACM (2005) 276–283

[154] Dubois-Ferriere, H., Grossglauser, M., Vetterli, M.: Age Matters: Efficient Route Discovery in Mobile Ad Hoc Networks Using Encounter Ages. In: Proceedings of MobiHoc '03, New York, NY, USA, ACM (2003) 257–266

[155] Akyildiz, I.F., Pompili, D., Melodia, T.: Underwater acoustic sensor networks: research challenges. Ad Hoc Networks **3** (2005) 257 – 279

[156] Chaintreau, A., Hui, P., Diot, C., Gass, R., Scott, J., Crowcroft, J.: Impact of Human Mobility on Opportunistic Forwarding Algorithms. IEEE Transactions on Mobile Computing **6** (2007) 606–620

[157] Zhang, X., Kurose, J., Levine, B.N., Towsley, D., Zhang, H.: Study of a Bus-based Disruption-Tolerant Network: Mobility Modeling and Impact on Routing. In: Proceedings of MobiCom '07, New York, NY, USA, ACM (2007) 195–206

[158] Costa, P., Mascolo, C., Musolesi, M., Picco, G.: Socially-Aware Routing for Publish-Subscribe in Delay-Tolerant Mobile Ad Hoc Networks. IEEE Journal on Selected Areas in Communications **26** (2008) 748–760

[159] Motani, M., Srinivasan, V., Nuggehalli, P.S.: PeopleNet: Engineering a Wireless Virtual Social Network. In: Proceedings of MobiCom '05, New York, NY, USA, ACM (2005) 243–257

[160] Sarafijanovic-Djukic, N., Pidrkowski, M., Grossglauser, M.: Island Hopping: Efficient Mobility-Assisted Forwarding in Partitioned Networks. In: Proceedings of SECON '06, Sensor and Ad Hoc Communications and Networks Conference. (2006) 226–235

[161] Musolesi, M., Hui, P., Mascolo, C., Crowcroft, J.: Writing on the clean slate: Implementing a socially-aware protocol in Haggle. In: World of Wireless, Mobile and Multimedia Networks, 2008. WoWMoM 2008. 2008 International Symposium on a. (2008) 1–6

[162] Hui, P., Yoneki, E., Crowcroft, J., yan Chan, S.: Identifying Social Communities in Complex Communications for Network Efficiency. In: Proceedings of Complex Sciences: Theory and Applications (Complex 2009), Shangai, China. (2009)

[163] Yoneki, E., Greenfield, D., Crowcroft, J.: Dynamics of Inter-Meeting Time in Human Contact Networks. In: Proceedings of International Conference on Advances in Social Networks Analysis and Mining (ASONAM), Athens, Greece. (2009)

[164] Erramilli, V., Chaintreau, A., Crovella, M., Diot, C.: Diversity of Forwarding Paths in Pocket Switched Networks. In: Proceedings of the 7th ACM SIGCOMM conference on Internet measurement (IMC '07), New York, NY, USA, ACM (2007) 161–174

[165] Buchegger, S.: Delay-Tolerant Social Networking. In: 1st Extreme Workshop on Communication (ExtremeCom 2009), Laponia, Sweden. (2009)

[166] Liu, C., Wu, J.: Scalable Routing in Delay Tolerant Networks. In: Proceedings of MobiHoc '07, New York, NY, USA, ACM (2007) 51–60

[167] Lindgren, A., Hui, P.: The Quest for a Killer App for Opportunistic and Delay-Tolerant Networks. In: Proceedings of CHANTS. (2009)

[168] Wood, L., Holliday, P., Floreani, D., Eddy, W.: Sharing the dream; the consensual networking hallucination offered by the Bundle Protocol. In: Proceedings of E-DTN '09, Workshop on the Emergence of Delay-/Disruption-Tolerant Networking, St. Petersburg, Russia. (2009)