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A taxonomy of congestion control and reliability approaches in opportunistic DTNs

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Abstract

Delay and Disruption Tolerant Networking (DTN) has been aiming to tackle the communication challenges originating from the lack of continuous end-to-end connectivity, for a diverse set of mobile/wireless networking environments and applications. Among its basic concepts, DTNs support data storage at intermediate hosts, as a means of application sessions surviving connectivity disruptions. To this end, delivery reliability can be ensured on a hop-by-hop basis for environments were the node contacts which offer communication opportunities are predetermined (*scheduled*). However, in a large majority of terrestrial DTN settings, the mobility patterns of the communicating peers lead to rather randomly occuring (*opportunistic*) contacts. In such conditions, ensuring reliable data delivery is more challenging and it might not be feasible to achieve based on the basic hop-by-hop paradigm. On top of that, buffer congestions taking place at the DTN nodes can worsen the situation. In the current report we review and classify existing congestion control and reliability approaches that exist in the literature, for opportunistic DTNs.

Index Terms

DTN, congestion control, reliability, scheduling, buffer management.

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1 Introduction

Disruption Tolerant Networks (DTNs) can be considered as a special type of MANETs which aims to provide communication services, when end-to-end data routing paths between the source and the destination cannot be maintained. Delay/Disruption Tolerant Networking [1] was initially dealing with communication challenges in Space (Interplanetary Deep Space, Satellite communications etc.). Such challenges usually refer to maintaining end-to-end data delivery alive when experiencing large propagation delays, or delays caused by periodic loss of line of sight conditions between the communicating peers. The application domain of DTNs has more recently been enriched with a large family of terrestrial networking environments, under networking conditions which have the same impact with the ones encountered in space communications: the loss of continuous end-to-end connections.

In order to survive intermittent connectivity, DTNs are based on the store-carry-and forward concept: the mobile nodes can store their own, or other nodes contents until some next communication opportunity appears, either with the destination (content delivery) or with some relay node to which they can convey data. Based on this principle, the DTN applications running on the end-hosts can remain transparent of the connectivity disruptions. However, the lack of continuous end-to-end connectivity, the limited communication opportunities, as well as the requirement for nodes to store their own and other nodes data in resource-constrained environments, makes it challenging to guarantee data delivery within a specific time limit. In parallel, these conditions can lead to congestion events at the nodes storage space. To this end, efficient data scheduling and storage congestion control are needed, during node contacts and buffer congestions respectively, to coordinate the distribution of limited resources in the network.

In the current report, we first describe the general DTN Architecture framework (section 2), focusing on the basic functions of the introduced *bundle* and *convergence layers*, which aim to survive intermittent connectivity and provide interconnection within heterogeneous sub-networks. These functions include the hop-by-hop custody transfer, as a means of ensuring data delivery, in the absence of end-to-end connectivity. Although this approach is functional for scenarios with predetermined topologies and scheduled type of contacts between the DTN nodes, it might not be adequate for challenging scenarios characterized by more random mobility patterns and dynamically changing topologies resulting in opportunistic contacts. In this context, we review and classify existing schemes in the literature for congestion control and reliability operations in such type of opportunistic settings (section 3). This classification is based on the associated networking environments, their objectives and their basic operation principles.

2 DTN Architecture

The DTN architecture [2] has initially been proposed to tackle the communication challenges appearing in interplanetary, deep space networks. However, the suggested framework was envisioned to consist the basis, on top of which, functional solutions for other types of networks (e.g., wireless terrestrial sensor networks, underwater, satellite) can be built, as well. Such networks may also suffer from intermittent connectivity, leading to frequent network partitioning and, eventually, the incapability of maintaining end-to-end connections active.

To overcome such obstacles, the DTN-architecture relies on a store-carry-and-forward, hop-by-hop or subnet-by-subnet data delivery strategy, depending on the length of the path which has to be traversed, before the transmitted data has to be locally stored to survive some sort of disruption. In Fig. 1, a simple scenario example leveraging from the DTN architecture is depicted. Based on this scenario, two of the intermediate nodes participating at the end-to-end data delivery path: i.e., custodian and moving data "ferry" nodes, have to store the data originating from a source node, until the next hop is discovered within communication range and the respective partitions are connected to the rest of the network. In this way, the end-to-end path to the destination can be split into multiple sub-paths. Apart from local connectivity disruptions, the need for intermediate storage and interconnection can be dictated by the presence of Heterogeneous sub-networks within the same network. In this context, heterogeneity can refer to different Network types (e.g. IP vs non-IP based subnets connected through gateway nodes, as shown in Fig. 1), or different locally experienced communication conditions (e.g. higher vs lower bandwidth radio interfaces). In such cases, compatibility with each Network specific stack (Fig. 2) is a prerequisite to provide seamless communication capability.

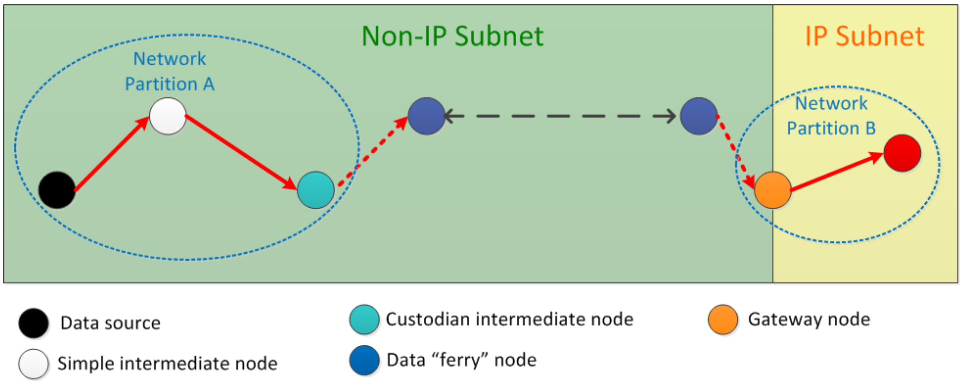

Figure 1: DTN scenario example

2.1 The Bundle and Convergence Layers

The Bundle layer is the basic novelty introduced by the DTN architecture, to support scenarios such as the aforementioned one. It constitutes a new sublayer within the application layer of the protocol stack, as shown in Fig. 2, where the majority of DTN operations are placed. These operations include the data storage capability at the intermediate nodes, data fragmentation operations, the hop-by-hop reliability strategy (discussed in section 2.2), as well as a general framework for supporting different QoS classes of service [3], [4]. Last but not least, based on the DTN Architecture, the bundle layer can integrate data routing, scheduling and congestion control intelligence within the intermittently connected parts of the network. The bundle protocol specification [3] specifies the "bundles" format. Bundles are data units which are constructed out of the Application Data Units (ADUs) and are generally supposed to be large and self-sufficient (i.e., include both data and all necessary metadata information), in order to avoid "chatty" negotiations with the receiver nodes and comply with the limited amount and duration of node contacts.

Based on the DTN Architecture, the DTN-related functionality implemented at the Bundle layer can be agnostic of the protocol stack lying underneath. To support this feature, the DTN architecture supports the existence of convergence layer adapters. The aim of these adapters is to provide appropriate interfaces to adapt the Bundle Layer's operation and requirements to the services and specification of the protocol stack which is available for each local network. As there can be a large variety of protocol families (e.g. IP vs non-IP, TCP vs User Datagram Protocol (UDP)-oriented for IP links), each respective convergence layer possibly needs to augment these protocols with necessary operations (e.g. message boundaries for TCP streams, reliability, congestion control, segmentation mechanisms for UDP). In this context, the co-ordination of bundle and convergence layer operations is envisioned to ensure the survival of communication disruptions and the interoperability among different network types (as highlighted in Fig. 1), respectively, while maintaining the applications running at the communicating ends transparent of the associated mechanisms.

2.2 Reliability and Custody transfer

Based on the store-carry-and-forward concept, **custody transfer** is the signaling mechanism which supports hop-by-hop (or subnet-by-subnet) reliability, by transferring the responsibility of a Bundle's delivery among the DTN nodes, throughout the path to its destination. This mechanism allows for the reliability operation to move closer to the destination DTN Node, following the transfer of the respective Bundle. Moreover, it allows for fast release of storage resources at the Bundle sources and at intermediate nodes after they transfer the custody to the next hop of the delivery path. Thus, reliability is supposed to cost much less in terms of re-transmissions, delivery delay, data rate and energy consumption. Indeed, con-

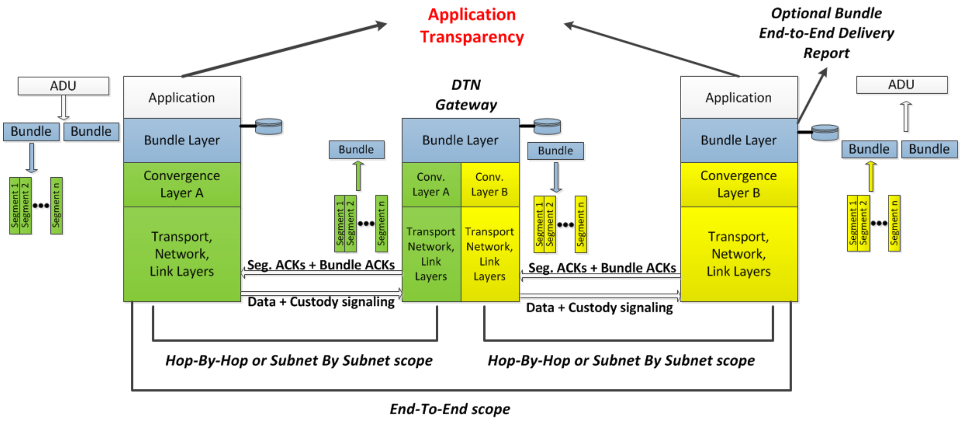

Figure 2: DTN architecture overview

sidering a bundle transfer failure occurring in some node close to the destination, it would be less costly to re-transfer the failed data from a neighbor node, than from the source node of the initial Bundle. Not all of the nodes throughout a route to the destination have to be custodians and the choice can be based on criteria such as: the amount of available resources that the candidate nodes possess (e.g. buffer space, Energy level) or the topology (e.g. Fig. 2 with DTN Gateway being a custodian). Based on [2], a custodian node should normally not be allowed to drop a Bundle under any buffer congestion event.

3 Taxonomy of Congestion control and Reliability approaches

In the following, we provide a classification of the congestion control and reliability approaches, existing in the literature. Our focus is on solutions for opportunistic contact networks. However, we start from reviewing approaches which target scheduled type of contacts and are more compliant to the DTN Architecture model. The aim is to highlight in which manner such approaches fail to capture the communication challenges in opportunistic networks.

3.1 Scheduled vs opportunistic contacts

Inter-planetary and satellite networks are the most characteristic case where the type of contacts between DTN nodes are typically **scheduled**. Due to the resulting predetermined topologies describing them, the main challenge is to deal with the instability of the links within the source to destination path and the large propagation delays. As shown in the example of Fig. 1, those links can be grouped in separate network partitions/subnets, residing between data storage points. In this context, within each native subnet, congestion control can be provided in more of a TCP-like manner. To this end, multiple transport and/or convergence layer protocols have been proposed, to provide congestion control and reliability functionalities.

A lot of these are TCP extensions which aim to adjust their congestion control functions, in order to comply with the aforementioned conditions (e.g. [5], [6], [7], [8], [9]). TCPCL [10] is a convergence layer protocol, provided to adopt TCP based protocols operation to the DTN architecture model and the requirements of the Bundle protocol. Other reliable protocols such as DS-TP [11] and NORM [12], [13] aim to apply congestion control in a more efficient manner than TCP, by decoupling the specification of the transmission rate at the sender from the delayed feedback (positive or negative ACKs) arriving from the receiver. Contrary to the aforementioned approaches, LTP [14], [15] and Saratoga [16], [17], [18] focus on point-to-point, data transfer at the link layer. Both protocols support data transport for concurrently running application sessions within the host nodes. Due to their local point-to-point nature and the deterministic means they use to fairly distribute the resources among the application sessions, they do not need to incorporate any congestion control mechanisms, unless interconnection of the links with the public Internet [19], [20] is required. Saratoga supports reliable data transfer, whereas in LTP both reliable and unreliable (UDP-like) data transfer is supported. LTP-T is an extension of LTP to operate in an end-to-end, instead of a point-to-point scope, constituting a multi-hop analog to LTP, as described in [21]. To this end, it integrates reliability through hop-by-hop custody transfer, as well as a simple congestion notification mechanism, based on identifying local storage congestions and notifying the involved peers about it.

Although the aforementioned approaches can tackle reliable data transfer and congestion control within environments with scheduled contacts, the situation changes when contacts become rather **opportunistic**, as in our cases of interest. Then, the main source of intermittent connectivity is nodes random mobility, resulting to topologies which change dynamically and in a non-deterministic way. As a result of these conditions, data transfer decisions have to be taken on a hop-by-hop basis. In this context, it would be rather infeasible to apply congestion control based on the aforementioned end-to-end manner. On the contrary, it is meaningful and important to apply *storage congestion control* at local node buffers. Existing storage congestion control, as well as reliability provision techniques in the literature are closely related to data routing and forwarding decisions. In the context of local decision making, the per bundle related information (e.g., remaining lifetime, priority, size, estimated probability/delay of delivery or further forwarding), as well as the locally (within a node's "neighborhood") experienced storage congestion volumes can be considered to optimize the delivery performance. From an architecture point of view, based on the DTN model, such techniques are usually considered as part of the bundle layer's functionality, as opposed to the previously reviewed transport/convergence layer protocols.

3.2 Single copy vs multiple copy routing

The discussion so far has been based on the assumption of a single copy of each bundle existing in the network at each time instant (i.e., **single copy routing**). Indeed, single copy routing and hop-by-hop reliability through custody transfer are generally preferred for scheduled contact networks, which lead to predetermined routing paths. Furthermore, it is often chosen in the context of probabilistic/opportunistic but densely populated networks (e.g., mobile social networks as described in the following), allowing to circulate up-to-date routing information and, at each hop, select the best among multiple relay choices. **Multiple copy routing**, on the other hand, can increase the delivery performance in opportunistic DTN settings. Moreover, it usually requires much less, or even no network topology information [22], comparing to single copy routing approaches. This attribute makes it attractive for a wide range of scenarios where it is hard to circulate and keep such information updated: e.g., sparsely populated networks and stressing communication conditions, on top of nodes mobility. However, multiple copy routing generally comes with the cost of easier resources exhaustion and consequently more frequent buffer congestions. In the context of storage congestion control for opportunistic DTNs, there exist both techniques which are based on single copy (e.g., [23], [24], [25] [26], [27], [28], [29], [30]) and multiple copy routing (e.g., [31] [32], [30], [33], [34], [35], [36], [37], [38], [39], [40], [41] [42], [43]) in the literature.

Among the ones running on top of single-copy routing, only few schemes are independent of the actual routing protocol (e.g. [24], [26]). For instance, Token Based Congestion Control (TBCC) [24] applies some sort of admission control by distributedly controlling the amount of traffic which is injected in the network, resembling the objective of congestion control of TCP-based protocols. On the other hand, multiple approaches, primarily focusing on social opportunistic networks, combine their congestion control and data forwarding strategies with exploiting routing information. Such information may refer to the *congestion level within a node's neighborhood* (e.g. [23], [25], [27], [28]) or some *social metric* which can indicate the relay nodes that lead to faster delivery (e.g. [25] [27], [28], [29]). CaFe [25] is one such approach which combines both these types of information to optimally select the next hop for a bundle's delivery.

Regarding congestion control with multiple copy routing, many popular protocols (e.g., [44], [45], [46]) are based on restricting the amount of replication, in order to decrease the overall congestion in the network, comparing to pure epidemic routing [22], while preserving higher delivery performance than single copy routing, in many scenarios of interest. However, they suggest rather static ways for limiting replication. In this context, determining optimal replication factors for dynamic opportunistic networks is a challenging task. To this end, congestion control techniques, which can dynamically adjust data replication decisions based on the experienced level of congestion in the network, are considered necessary.

A wide range of such existing techniques is *independent of classic routing information related to destination-based*, best relay selections (e.g. [31], [32], [30], [38], [39], [41], [42], [43]). Instead, their resources distribution methods, can be classified based on whether they use some sort of *replication* or *buffer dropping management*, or both, as in [31], [32], [41], [42], [43]. Replication management techniques can be further categorized to those adjusting their replication factors based on the cooperatively experienced congestion volumes at the DTN nodes (i.e., *node-based experienced congestion*) (e.g., [30], [38], [40]) and those that determine the degree of replication on a *per bundle* basis, based on bundle-specific (non-destination related) information (i.e., remaining lifetime, priority, bundle size, number of copies etc.) (e.g., [31], [32], [39], [41], [42], [43]). The former approach is based on some type of storage congestion indications originating from a node itself, or considering also relative information from its neighbor nodes. Based on such indications, each node locally and dynamically determines the degree of replication which is applied on equal terms among the stored data. The latter approach is considered more attractive when there is the need for replication and dropping decisions in different terms, depending on the relative priority among different data. Global Knowledge Based Scheduling and Drop (GBSD) and History Based Scheduling and Drop (HBSD) [32] rely on both bundle-based replication management (scheduling) and dropping, to optimize resources distribution during limited contact durations and buffer congestion events, respectively. Particularly, these policies are based on deriving per bundle utilities which express each bundle's marginal value, with respect to the network's optimization metric of interest (i.e., delivery rate maximization, or delivery delay minimization). Moreover, they operate on top of epidemic routing. Without excluding the use of other multi-copy routing protocols, selecting greedy epidemic routing underlines more the performance value of the specific approach, since it demonstrates its efficiency under the most stressing conditions. In [41] a variant of the GBSD and HBSD schemes is proposed based on the same framework of per message utilities but designed to operate on top of binary Spray and Wait, instead of Epidemic routing.

3.3 Congestion control objective

In the context of single copy routing and hop-by-hop custody transfer, although buffer congestions are expected to be less frequent than with multiple copy routing, their effects are relatively more detrimental for the network performance, than with multiple copy routing. Indeed, if a node has to drop a bundle for which it has accepted the custody, then this bundle will surely not be delivered, since there will be no way for the source node to get informed and re-transmit it. Hence, multiple storage congestion control techniques on top of single copy routing mainly aim to *avoid congestion events* (e.g., [23], [24], [25], [27], [28]).

On the contrary, congestion control techniques based on multiple copy routing may refer either to *congestion avoidance* (e.g., [30], [33], [35], [36], [37], [38]), or *congestion management* (e.g., [31], [32], [34], [39], [41], [42]), or both (e.g.,

[40], [43]) aiming to minimize the negative effects of buffer congestions, once they occur. Since multiple replicas of the same data can co-exist in the network, the impact of dropping bundle copies can be significantly lower, if the copies to get dropped are chosen optimally with respect to some network performance metric(s). Accordingly, the benefits of bundles replication can be maximized, if the bundles to get replicated during limited contact durations are picked optimally, based on criteria as those described before.

3.4 Reliability and data acknowledging objective

As already discussed, traditionally reliability refers to the capability of always ensuring successful data delivery at the initial source (end-to-end scope). This capability strongly depends on the utilized acknowledging mechanism (ACKs). The ACKs are usually short control packets which traverse the network on the reverse path, with the aim of reaching the initial packet source and inform it about the successful delivery of the respective data packet at the destination. In DTNs, however, the acknowledgments aim to provide reliability either on a **hop-by-hop** (subnet-by-subnet) basis, or on an **end-to-end** basis. Although the former consists the basic alternative to traditional end-to-end reliability for DTNs [2], [47], its efficiency is questionable for non-scheduled contact scenarios which might lead to unexpected bundle drops at custodian nodes. STRAP [48] is based on custody delegation to provide hop-by-hop reliability to multicast opportunistic networks. In this context, it requires to maintain per bundle delivery state information at the DTN nodes and circulate it in the network. Hop-by-hop custody transfer is also not appealing to combine with multiple copy routing schemes, due to the increased complexity and associated overhead of keeping track of multiple paths and/or sub-paths. End-to-end reliability approaches, on the other hand, are always challenging to provide, due to the absence of end-to-end connectivity, let alone in the framework of opportunistic scenarios. In this context, some of the existing approaches provide **best effort mechanisms for end-to-end reliability** (e.g., [49], [50], [51], [52]), while others intend to **guarantee end-to-end reliability** (e.g., [53], [54], [55]). The main differentiation point among the two categories has to do with how each one performs when delivery time limits are imposed. Although best effort approaches can ensure 100% delivery ratio when there are no time restrictions imposed on the data delivery, they cannot do the same when such restrictions are present [49]. The aim of guaranteed approaches, on the other hand, is to ensure this ratio even under time constraints.

To this end, the aforementioned guaranteed schemes combine network coding with ACK mechanisms. Network coding generally allows to encode and merge multiple individual packets in a single one, permitting to increase the amount of data that flows in the network and decrease the required resources per packet. As a result, its use is quite popular with DTN solutions. Ali et al. [53] are based on retransmission cycles to guarantee end-to-end reliability, while the use of Random Linear Combinations (RLCs) of individual packets assists in reducing the amount of retransmitted data and minimizing the overall data transfer time. In [54] they extend their approach to account for both unicast and multicast delivery, as well as for supporting multiple sessions launched concurrently in the network. Such approaches seem promising for guaranteeing end-to-end reliability in opportunistic settings. However, the fact that their evaluation is based on a relatively small number of individual sessions running between source-destination pairs, raises some scalability concerns about how they would respond to a larger amount of concurrent sessions in the network. Accordingly, from a mobility perspective, they lack some assessment with real rather than synthetic mobility, to better validate their performance in opportunistic settings.

Reliability is not the only role of acknowledging mechanisms. ACKs can also be used as means of closed loop congestion control, by **releasing network resources** (e.g., [49], [52], [56]) which are attributed to bundles that have already been delivered (e.g., buffer space, redundant future bandwidth/energy consumption for replicating such packets). This role is more important when multiple copy routing schemes are used and, as a result, the amount of utilized resources per packet in the network is much larger than in the case of single copy routing.

3.5 ACK dissemination scheme

However, given the limited amount of resources and communication opportunities, the dissemination of data ACKs can consist a significant source of overhead in the network. In this context, existing schemes intending to capture one or more of the aforementioned reliability objectives, incorporate different ACK dissemination approaches.

In [49] Harras et al. suggest some basic alternatives, aiming to operate on top of multiple copy data routing. Active and Passive receipt are two best effort reliability and resources releasing schemes, based on spreading multiple copies of each ACK in the network. The two approaches differ in the “aggressiveness” in which they spread the ACKs. Active Receipt is based on **Epidemic routing** (as [50], [51], [53]) and thus induces more control traffic in the network comparing to Passive receipt. The latter disseminates the ACKs only to nodes which are “infected” with the respective data that ACKs are targeting, thus constituting a **selective** way of replication. This however comes with the trade-off of increased queueing time of the initial data at the DTN node buffers, comparing to Active Receipt. In an attempt to balance this trade-off, Congestion Level based end-to-end ACKnowledgement (CL-ACK) was proposed as an extension of the aforementioned approaches, which switches dynamically between Active and Passive receipt, based on the measured congestion level (i.e. message drops/message replications). Another technique used to increase the efficiency of feedback dissemiation is **ACKs aggregation** (e.g., [54], [55]): multiple ACKs aggregated to single messages, as a means of reducing the overhead of utilized resources and achieving faster spreading. In [54] the following aggregation attributes are used: the inclusion of multiple ACKs to a single Selective ACK (SACK) which acknowledges the reception of multiple messages from different sources at a specific destination; The Global Selective ACK (G-SACK) which is produced by merging the contents of multiple SACKs traversing the Network.

3.6 Considering multiple QoS classes

Multiple of the previously reviewed schemes aim to optimize resources distribution in the context of congestion control and reliability provision. However, they generally consider application sessions of equal priority (i.e., of a single QoS class). However in multiple application environments there might the need to support multiple services in parallel, which belong to different QoS classes and correspond to different sets of QoS requirements.

Based on the bundle protocol [3], there is provision for three different QoS classes: Expedited (high priority), Normal (medium priority) and Bulk (low priority) by the DTN community [1]. More recently there has been an extension to support more priority levels within the Expedited class [4]. While such QoS classes provide a static characterization of different classes of messages, prioritization decisions among bundles belonging to different classes is an open issue. In this context, a few existing schemes claiming to address the problem of QoS prioritization, do so by reserving a fixed proportion of resources to each class based on its relative priority comparing to the others (e.g. [57], [58]), or by being based on some kind of heuristic approach e.g., [59].

4 Conclusions

In the current report, we first highlighted the different communication challenges appearing in distinct types of DTN environments. In this context, we described how the nodes mobility and contact patterns influence the solutions space, with respect to ensuring reliable data delivery. To this end we reviewed and classified different congestion control and reliability approaches that exist in the literature, starting from scheduled contact DTNs and focusing more on opportunistic ones.

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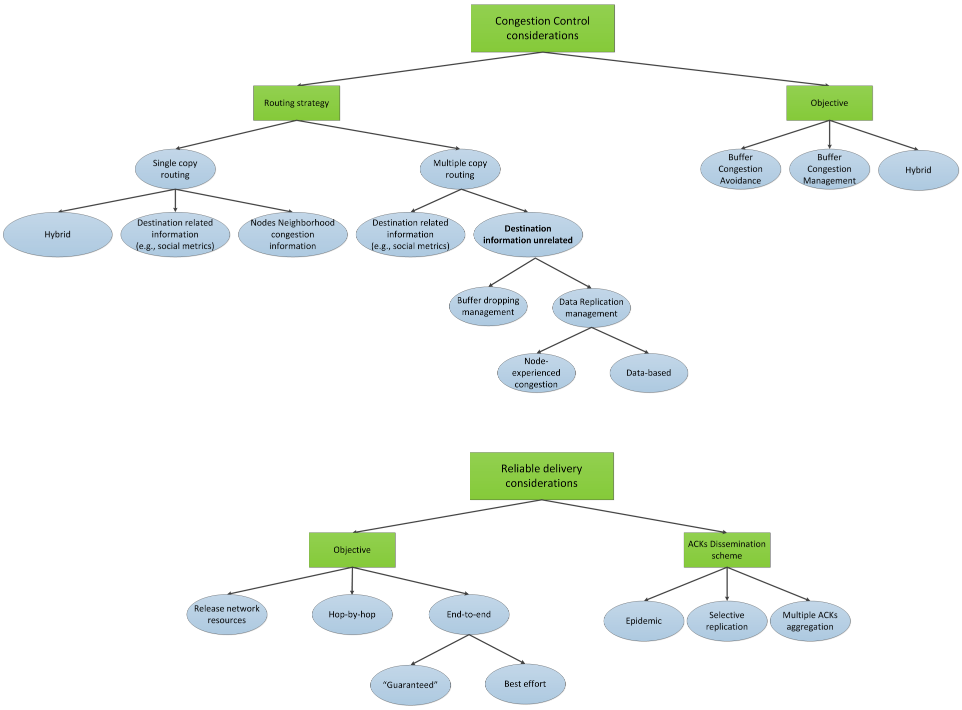

Figure 3: Taxonomy of congestion control and reliability considerations for opportunistic DTNs

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