Congestion Aware Routing Strategies for DTN-based Interplanetary Networks

Igor Bisio and Mario Marchese
Department of Communication, Computer and System Sciences, University of Genoa
Via Opera Pia 13, 16145, Genoa, Italy
{igor.bisio, mario.marchese}@unige.it

Tomaso de Cola
DLR- German Aerospace Center
Institute for Communications and Navigation
82234 Wessling, Germany
tomaso.decola@dlr.de

Abstract — The networking and communication challenges posed by interplanetary environments make the design and the deployment of complex telecommunication infrastructures particularly difficult, especially with regard to routing and congestion control issues. To this end, the paper proposes a congestion-aware routing paradigm that applies Multi Attribute Decision Making (MADM) concepts for next-hop selection, by formulating an optimisation problem and proposing some possible resolution criteria. Effectiveness of the proposed solutions is assessed through a preliminary performance analysis that shows promising results.

Index Terms – Interplanetary Networks, Congestion Control, Next-Hop selection, Delay Tolerant Network architecture.

I. INTRODUCTION

O

VER the last years, the interest for space networking has fostered the study and the design of novel transmission paradigms, tailored to the harsh communication conditions experienced in this environment [1]. In particular, the performance limitations shown by TCP-based protocols over interplanetary networks in consequence of large propagation delays as well as consistent information losses opened the doors to the design of more effective protocol architectures [2]. In more detail, particular effort has been made by standardisation bodies such as the Consultative Committee for Space Data Systems (CCSDS) and the Delay Tolerant Networking working group within the Internet Research Task Force (IRTF). The former developed a full protocol stack, alternative to the TCP/IP Suite, specifying protocol layers, from the application downwards to the physical, more appropriate to the deep space peculiarities [3]. The latter has devised an overlay network architecture named Delay Tolerant Architecture (DTN), working over the transport layer and able to tolerate link disruptions and long delays, owing to the features offered by the Bundle Protocol [4].

In spite of the relevant efforts made by the scientific community, some research areas are still only partially explored. In more detail, some attention has to be drawn to the performance issues related to the transport layer, in terms of recovery procedures and congestion control schemes. In fact, several proposals attempting to address reliability issues have been worked out recently. Akyildiz et al. [5] developed TPLEX, a new transport protocol, building on Additive Increase Multiple Decrease concepts, able to cope with blackout events by taking advantage of probing packets. In turn, the case of unavailable return links is addressed in [6], where reliability of communication is ensured by using appropriate erasure codes. Yet, Modiano et al. [7] approach the problem through Dynamic Programming formulation.

On the contrary, the study of congestion control over deep space networks has received much less attention. Burleigh et al. [8] investigated the problem of congestion events occurring at deep space gateways and proposed a call-admission-control scheme, relying upon economics concepts. Marano et al. [9] designed a hop-by-hop flow control scheme for Delay Tolerant Network architectures. Fall et al. [10] proposed an extension of Delay Tolerant Network architecture paradigm to cope with congestion events in wireless networks suffering from frequent link disruptions. In more detail, the authors show that congestion events can be efficiently managed by performing an effective storage routing, which actually consists in selecting the best next-hop to which forward messages. Although the environment analysed in [10] shows physical peculiarities that differ from those commonly experienced in an interplanetary scenario, explored in this paper, the idea of next-hop selection is very attracting. In fact, the need for optimising at the same time different performance indicators (i.e., message completion rate, data transfer time and power consumption), suggests a vector-optimisation formulation, which builds on Multi Attribute Decision Making (MADM) concepts [11]. In this light, this work explores the potentials of MADM methodology for performing next-hop selection over congested deep space networks [12].

The remainder of this paper is structured as follows. Section II introduces the general framework, by giving an overview of the protocol architecture and the reference scenario. Section III considers the general system model and the mathematical formulation of next-hop selection based upon MADM strategy. A preliminary performance analysis of the proposed solutions is given in Section IV, whereas the discussion of results and final remarks are drawn in Section V.

II. GENERAL FRAMEWORK

A. Delay Tolerant Network (DTN) architecture

This work takes as reference the Delay Tolerant Network architecture [4], which basically consists in the Bundle Protocol layer implemented under the application layer and running directly over transport, network or datalink layers. It fragments messages coming from the application layer (where present) into smaller units, commonly referred to as bundles. The main feature is represented by the custodial transfer option that allows suspending and resuming data transfer.

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sessions. Furthermore, the availability of administrative notifications (reports) as well as allows inferring the network state on the basis of the number of correctly received bundles.

In this work, we assume that the Bundle Protocol Layer does not make use of the custodial transfer option; therefore, communication reliability has to be ensured by proper mechanisms implemented at the underlying layers. Finally, we consider that the Bundle Protocol acts directly over the datalink layer, which implements the Licklider Transmission Protocol (LTP), detailed in the next section.

B. Licklider Transmission Protocol and Physical Layer Protocols

The Licklider Transmission Protocol (LTP) [13] is a point-to-point protocol basically implemented at the datalink layer and responsible for transferring data reliably over deep space links. It implements a recovery procedure, consisting in a Selective-ARQ strategy, which allows retransmitting all the LTP units (hereafter packets) missing at destination. The packets are classified into either red or green information blocks. Red blocks are usually characterised by strict reliability constraints: in case of information loss detection, selective retransmission of missing packets is performed. On the other hand, the information blocks that either 1) are tolerant to some information loss or 2) require high priority forwarding, are classified as green. In case of loss, they are not retransmitted. In this work, the only case of red blocks is considered.

As far as physical layer protocols are concerned, it is necessary to distinguish between deep space and proximity links: the former allow data communications between nodes that are very far with each other and experience a propagation delay as high as several seconds. The latter are commonly established between nodes that are in proximity one with another and whose propagation delay is lower than one second. On the basis of this differentiation, two protocol choices have been performed: in the case of deep space links, the CCSDS Telemetry/Telecommand Protocols (TC/TM) [3] have been taken as reference, whereas the CCSDS Proximity-1 Link Protocol [3] has been considered for the case of proximity links.

C. Reference Scenario

The scenario considered in this work (depicted in Fig. 1) is composed of two main portions: planetary and backbone regions. In more detail, each planetary region comprehends planetary nodes (white circles) working as both traffic source and destination nodes. The backbone region is composed of interplanetary nodes (black circles), serving as relay nodes, connected one with another through a mesh topology. Finally, specialised gateway nodes (grey nodes), responsible for data forwarding, connect the planetary regions. Fig.1 reports the case of 4 planetary regions, composed of two planetary nodes. Nodes 0, 9, and 10 are assumed as traffic source, nodes 1, 4, and 6, as destination, whereas 3 and 7 can both transmit and receive data. Finally, nodes from 12 to 17 belong to the backbone region; 2, 5, 8, and 11 are gateway nodes.

As far as the protocol stack of each node is concerned, a full DTN architecture working over LTP protocol is assumed in this work. LTP is responsible for point-to-point retransmission procedures that take place upon packet loss detection; the Bundle Protocol takes care of storing and forwarding data amongst regions. In this light, the role played by the Bundle Layer buffer is topical: on the one hand, saturation of buffers may cause long data queuing times and, lastly, loss of bundles, thus leading to an increase of the overall data transfer time. On the other hand, reactive management of congestion events is not applicable in this context because of the large latencies, which give rise to delayed congestion control decisions. In order to overcome the limitations of a reactive management, this work proposes a proactive strategy relying upon next-hop selection formulation, aimed at optimising both routing and congestion control strategies.

III. THE NEXT-HOP SELECTION FORMULATION

As pointed out in Section II-C, the overall system performance is strictly dependent on effective management of Bundle Layer buffers. To this end, a congestion-aware routing algorithm has been formally defined by exploiting the features of Multi Attribute Decision Making theory. In more detail, the proposed algorithm performs, for each queued bundle, a next-hop selection aimed at computing the best path on the basis of performance metrics, such as bundle layer buffer occupancy and bandwidth availability.

A. The MADM Approach

The aim of the proposed approach is to select the Next-Node towards which bundles have to be forwarded. The decision is performed by virtual entities called Decision Makers (DMs), implemented within each node. Let \( DM^{(n)} \) denote the Decision Maker for node \( n \). It selects the Next-Hop to which the bundles have to be forwarded. This selection is implemented periodically, in order to effectively adapt the routing strategies. Yet, let \( T_{D,h}^{(n)} \), \( n \in [1,N] \), \( h \in \mathbb{N} \) denote the decision period for node \( n \). It selects the Next-Hop to which the bundles have to be forwarded. This selection is implemented periodically, in order to effectively adapt the routing strategies. Yet, let \( T_{D,h}^{(n)} \), \( n \in [1,N] \), \( h \in \mathbb{N} \) denote the selection period, where the decision is valid for the overall length of the \( h \)-th decision period for node \( n \), which is kept fixed \( \forall h, \forall n \). Within each \( T_{D,h}^{(n)} \) period, the neighbours of node \( n \), notify it about their congestion levels in terms of proper metrics, defined as Quality of Service requirements.

Being the mentioned metrics possibly in contrast each other (i.e., increasing one may imply decreasing another), the
selection algorithm is conveniently based on the Multi Attribute Decision Making (MADM) [11]. Let index \( k \in [1, K] \) identify the metrics (e.g., bundle layer buffer occupancy, bandwidth availability), \( j \in [1, J] \) any possible Next-Hop (selection alternatives) for a generic node \( n \) (where the decision algorithm is applied). Let each \( DM^o_n \) be characterised by a decision matrix: \( X^n_{jk}(t) \) is the value of the metric \( k \) measured at the time instant \( t \) for the node \( n \) when Next-Hop \( j \) is used. Let \( X^n_{jk}(t) = X^n_{jk}(t)/\max X^n_{jk}(t) \) be the normalized metric (attribute hereafter) over its maximum measured value.

B. The Selection Algorithm

In this paper, three possible approaches, directly taken from the MADM basic theory, are proposed and evaluated: Simple Additive Weighting (SAW) [11], Minimum Distance with Utopia Point (MDUP) [12], and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [11, 14].

The principle of the SAW selection algorithm is to minimize the sum of all the attributes of interest. In practice, amongst the \( J \) alternatives, the selection algorithm chooses the Next-Hop denoted as \( f_{opt}^{n,SAW}(t) \), as follows:

\[
f_{opt}^{n,SAW}(t) = \left\{ j^n = \arg \min_{j \in [1, J]} \sum_{k=1}^{K} X^n_{jk} \right\}
\]

(1)

The MDUP selection algorithm is based on the knowledge of the ideal alternatives, called utopia point, characterized by the utopia vector of attributes at the time instant \( t \), whose component are defined in (2), where the superscript \( id \) stands for ideal:

\[
id X^n = \left\{ \begin{array}{l}
X^n_{jk} : j = \arg \min_{\in [1, J]} X^n_{jk}, \text{ for } "cost" \text{ metrics} \\
X^n_{jk} : j = \arg \max_{\in [1, J]} X^n_{jk}, \text{ for } "benefit" \text{ metrics}
\end{array} \right.
\]

(2)

In practice, the utopia vector contains both “cost” (e.g., the bundle layer buffer occupancy) and “benefit” metrics (e.g., the bandwidth availability). To this regard, it is immediate to see that the utopia vector allows selecting the best value for each single attribute amongst all the alternatives, by taking the minimum and the maximum of cost and benefit metrics, respectively. More precisely, the Next-Hop selection algorithm chooses the Next-Hop called \( f_{opt}^{n,MDUP}(t) \) amongst the \( J \) alternatives, by minimizing the distance, in terms of Euclidean norm, from the ideal alternative:

\[
f_{opt}^{n,MDUP}(t) = \left\{ j^n = \arg \min_{\in [1, J]} \left[ \sum_{k=1}^{K} \left( X^n_{jk} - id X^n_k \right)^2 \right]^{1/2} \right\}
\]

(3)

The TOPSIS selection algorithm extends the concepts applied by the MDUP scheme, by taking advantage of the knowledge of both the utopia points defined in (2) and the nadir points, which, on the contrary, represent the worst alternatives. Definition of nadir points basically inverts the formulation of ideal ones, by considering the maximum and the minimum for cost and benefit metrics, respectively.

The Next-Hop selection algorithm chooses the Next-Hop called \( f_{opt}^{n,TOPSIS}(t) \) amongst the \( J \) alternatives, by minimizing the so called Similarity to Positive-Ideal Solution (4):

\[
f_{opt}^{n,TOPSIS}(t) = \left\{ j^n = \arg \min_{\in [1, J]} \frac{S^n_{j}^p}{S^n_{j}^p + S^n_{j}^m} \right\}
\]

(4)

where \( S^n_{j}^p \) is the distance, in terms of Euclidean norm, between the alternatives and the utopia point called Positive Separation; \( S^n_{j}^m \) is the distance between the alternatives and the nadir point called Negative Separation.

C. The Proposed Solutions

Although the validity of the mathematical framework is general, in this work the attention has been paid to a reduced set of metrics: Bundle Buffer Occupancy (BBO), Available Bandwidth (AB), and Transmission Time (TT).

The Bundle Buffer Occupancy is the ratio between the number of bundles stored in the bundle layer buffer and the maximum size of the buffer itself. \( BBO_j^{(n)}(t) \) is the value of this attribute, valid at the time instant \( t \), for node \( n \), notified from its neighbour \( j \). In short, \( BBO_j^{(n)}(t) = X_{j1}^{(n)} \) and it represents a “cost” attribute.

Available Bandwidth (AB), is the capacity in [bit/s] available on the links between node \( n \) and its neighbour \( j \). As observed in the previous case: \( AB_j^{(n)}(t) = X_{j1}^{(n)} \) but, here, it represents a “benefit” attribute.

Alternatively to Average Bandwidth, the Transmission Time (TT) attribute can be used. In fact, it is the ratio between the bundle size (expressed in bit) and the link capacity in [bit/s] available in link between node \( n \) and its neighbour \( j \). In this case, we have: \( TT_j^{(n)}(t) = X_{j2}^{(n)} \) corresponding to a “cost” attribute.

The corresponding Congestion Aware Routing techniques can then be classified into three main classes, depending on the applied MADM strategy (SAW, MDUP, TOPSIS). In particular the combinations of Bundle Buffer Occupancy with Available Bandwidth, and Bundle Buffer Occupancy with Transmission Time have been considered for all the possible MADM approaches, thus resulting in six different solutions: SAW-BBO-AB, SAW-BBO-TT, MDUP-BBO-AB, MDUP-BBO-TT, TOPSIS-BBO-AB, and TOPSIS-BBO-TT. In addition, also traditional mono-attribute schemes are considered for the SAW strategies: SAW-BBO and SAW-TT.

IV. PERFORMANCE ANALYSIS

The evaluation of the proposed solutions has been performed through ns-2, by properly extending the DTN modules and implementing the Decision Making entities within the Bundle Protocol layer. In particular, we assumed that operations of attribute notifications amongst nodes and related neighbours take negligible time with respect to simulation duration. Moreover, the attribute exchange period \( T_{D,h}^{(n)} \) has been set to 50 s \( \forall n \in [1, N], \forall h \in \mathbb{N} \). Finally, for the sake of simplicity, the MADM-based routing capabilities have been implemented just on the interplanetary backbone nodes.
whereas the other nodes implement static routing schemes. This assumption does not limit the validity of this study because, commonly, nodes either belonging to the planetary regions or serving as gateways implement large storage units, which therefore prevent from congestion events and then make the use of MADM techniques unnecessary.

The performance analysis has been conducted by taking network topology depicted in Fig. 1 as reference. In more detail, the propagation delay amongst interplanetary backbone nodes has been set to 20 s. The (full-duplex) capacities of link connecting backbone and gateway nodes are summarised in Table I (in Kbit/s). Moreover, each node implements a bundle layer buffer size equal to 400 bundles. On the other hand, the propagation delay between planetary nodes and gateway nodes has been set to 0.5 s, whereas the available link capacity to 2 Mbit/s. Constant Bit Rate (CBR) traffic sources are considered: they are kept active for 150 s of simulation and generate data bundles of 64 Kbytes at rate of 4 bundles/s, yielding 2.048 Kbit/s. Furthermore, the traffic sources have been set on the planetary regions, as introduced in Section II-A. In particular, nodes 1, 3 and 7 send data encapsulated into Non Custodial Transfer bundles, whereas nodes 0 and 10 generate inject background traffic into the network, in order to assess the robustness of the proposed MADM-based solutions. All the other planetary nodes are set as receivers. The simulation duration was of 10000 s for each test.

The performance analysis has been two-fold: Microscopic and Macroscopic. In the former, attention has been paid to the protocol performance experienced within each node. To this end, two specific metrics have been introduced to assess the effectiveness of the proposed congestion-aware routing mechanisms: Bundle Buffer Queue Length (BBQL) and Bundle Buffer Filling Rate (BBFR). BBQL figures give indications on how congestion events are likely to occur. On the other hand, BBFR gives a measure on how fast bundle buffer queue increases. In the case of Macroscopic Analysis, the investigation looks into performance provided by the whole network. In this light, two metrics have been considered: Bundle Loss Rate (BLR) and Data Delivery Time (DDT). The first is defined as ratio between the number of received and of transmitted bundles. The second accounts for the time interval required to complete the data delivery to destinations.

A. Microscopic Analysis

The analysis of Bundle Buffer Queue Length (BBQL) provides meaningful insights into dynamics of congestion control schemes within each node. For the sake of brevity, we limit here our analysis to the case of node 15 (shown in Fig. 2), which, reproduces to some extent the protocol dynamics observed also on the other nodes.

The BBQL behaviour over time shows that all the protocol solutions apart from SAW-BBO-AB give rise to a buffer queue length spike, registered around 500 s. In particular, it is worth noticing that TOPSIS-BBO-AB, TOPSIS-BBO-TT and MDUP-BO-AB provide the most meaningful results, by keeping the buffer length below 300 bundles. The mono-attribute solutions (SAW-BBO, SAW-AB), by contrast, perform poorly and saturate the buffer capacity (400 bundles). Finally, the case of SAW-BBO-AB deserves some attention. In the first phase of simulation (before 1000 s) we noticed that it performs very well by achieving a buffer queue length of about 50 bundles. Afterwards, BBQL for SAW-BBO-AB increases almost linearly with time, whereas the other solutions are most effective in making the appropriate routing decisions, leading to BBQL values close to 0.

Furthermore, if we consider the average bundle buffer queue length, depicted in Fig. 3, we can observe that TOPSIS and MDUP solutions outperform the other solutions since they are able to equalise the buffer queue length amongst all the nodes and to keep average BBQL below 10 bundles. In this light, also SAW-BBO-TT is promising, although it gives rise to average BBQL values higher than those observed for TOPSIS and MUDP solutions.

Finally, analysis of Bundle Buffer Filling Rate (BBFR) values deserves some attention. For the sake of brevity, we explore only the case of TOPSIS-BBO-TT, which actually offered the best results. It was observed that this protocol...
solution is able to maintain the buffer filling rate below 4 bundles/s in the first simulation phase, during which traffic sources are active.

Afterwards, as previously pointed out, all the node’s buffer queues are equalized thus leading to BBFR values below 1 bundle/s. It is also important to highlight that this solution is able to efficiently track network state variations, as experienced between 1500 s and 2000 s: the buffer filling rate slightly increases because of routing changes, and afterwards, BBFR keeps again below 1 bundle/s.

B. Macroscopic Analysis

The macroscopic analysis partially confirms findings of the microscopic analysis. In particular, it is possible to observe from Fig. 4, showing the Bundle Loss Rate (BLR %) performance that TOPSIS-BBO-TT outperforms the other solutions, achieving a BLR value of 0.06, far below numerical values offered by the other proposals. Also SAW-BBO and MDUP solutions are quite effective and offer satisfactory values of BLR (below 0.08). Finally, as one might draw from microscopic analysis, SAW-BBO-AB performs poorly, giving rise to a Bundle Loss Rate of about 0.53.

On the other hand, as far as Data Delivery Time (DDT) is concerned, it can be observed from Fig. 5 that both TOPSIS and MDUP solution offer promising solutions, thus confirming the added-value of a MADM approach. Finally, it is also worth noting that SAW-BBO and SAW-BBO-TT as well offer very satisfactory results; nonetheless, it is important to remark (see Fig. 5) that the reduced delivery time with respect to other solutions is achieved at cost of higher bundle loss rate.

V. CONCLUSIONS

This work focused on routing and congestion control issues in interplanetary environments. Taking as reference findings of [10] and features offered by MADM theory [11], two novel classes of solutions named TOPSIS and MDUP have been devised and evaluated through simulative campaigns, by taking into account also traditional techniques relying upon either mono-attribute or attribute weighted sum formulations. The performance analysis showed within both microscopic and macroscopic investigations that TOPSIS and MDUP solutions are really promising, in terms of tolerance to congestion events and effective routing decisions. In fact, advantages offered by MADM approach are far more evident in the case of TOPSIS implementations (particularly for TOPSIS-BBO-TT), which, on the one hand, achieved very good results in terms of bundle loss rate and data delivery time, and, on the other hand, showed adaptability features against congestion events as well as network state changes, as BBQL and BBFR figures highlighted.

REFERENCES