Combined Congestion Control and Link Selection Strategies for Delay Tolerant Interplanetary Networks

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Abstract — **In view of the dense and complex space network topologies envisioned for the future, the management of congestion control is a prominent issue that deserves a particular attention. Given the challenging peculiarities of interplanetary environments, this paper focuses on the advantages offered by storage-based routing and on potentials of implementing Random Early Detection (RED) and Explicit Congestion Notification (ECN) mechanisms within the Delay Tolerant Network (DTN) architecture. In this light, solutions relying upon the aforementioned concepts have been designed and tested. Preliminary results show that combination of RED and ECN schemes with network-selection strategies for storage-based routing is really promising and outperforms other solutions in terms of reliability, network resource utilisation and power consumption.**

Index Terms – **Interplanetary Networks, Random Early Detection, Explicit Congestion Notification, Delay Tolerant Network architecture, Custodial Transfer.**

I. INTRODUCTION

THE success of the Delay Tolerant Network (DTN) architecture, registered in both social applications (e.g., public protection and disaster relief) and deep space communications, paved the way for the design of complex network infrastructures in very challenging environments [1]. A case particularly interesting is represented by interplanetary scenarios, where effectiveness of data communication, in terms of network resource utilisation and power consumption, is hampered by physical medium peculiarities. In fact, long propagation delays, large error ratios, asymmetric and scarce channel bandwidths pose important limitations to the performance figures that should be expected in these environments. Besides, the demand for more complex space network topologies, suited to enable a tight integration between current Internet and interplanetary networks, provides further challenges in the design of future space telecommunication infrastructures. Just to cite a few, congestion control mechanisms and management of Quality of Service (QoS) are undoubtedly important points to be taken into account. As far as the former is concerned, it is important to point out that the present space network configurations, the topology being composed of a very limited number of nodes and data transmissions being scheduled in strict advance, can hardly suffer from congestion events, which in turn are more likely to occur in the terrestrial Internet. Nevertheless, the authors of this paper claim that congestion control and QoS management issues will play an important role in future space communications, where complex network topologies are expected to be deployed as envisioned in NASA plans [2] and already partially shown in some preliminary tests [3]. In practice, it is expected to deploy satellite constellations serving as relay points for storing data coming from planetary stations and for forwarding them towards Earth gathering centres through multi-hop deep space links. In this scenario, the necessity of advanced networking and communication protocols is straightforward, since the use of TCP/IP suite results inappropriate due to long propagation delays and large error ratios. To this end, the features offered by protocols recommended by the Consultative Committee for Space Data Systems (CCSDS) and the Delay Tolerant Network architecture are really promising to transfer data effectively over interplanetary networks. On the one hand, CCSDS developed a protocol stack, specifically tailored to space environments, from the physical to the application layer. On the other hand, the Delay Tolerant Network working group within Internet Research Task Force (IRTF) designed an overlay protocol architecture able to cope with long delays and frequent link disruptions, owing to advanced store-and-forward features (i.e., *custodial transfer* option). Despite the large standardisation effort carried out by CCSDS and DTN, important implementation gaps concerning QoS and congestion control management still need to be addressed. Actually, few contributions from the space scientific community have been worked out over the last years. Akyildiz *et al*. [4] designed TP-PLANET and RCP-PLANET protocols aimed at efficiently transferring data and multimedia over deep space links: a congestion control scheme applying Additive-Increase Multiple-Decrease (AIMD) concepts is here developed. Grieco *et al.* [5] propose an extension of TCP congestion control by introducing a novel rate-based scheme. A completely different approach is instead pursued by Bureleigh *et al.* [6], who developed a new congestion control scheme relying upon main findings of economics theory, in terms of portfolio and investment of assets. An important contribution to congestion control schemes suited to delay tolerant networks can be also found in [7], where the concept of alternative custodial transfer option is introduced to perform storage-based routing, which basically consists in selecting alternate next-hop depending on the storage capacity available on nodes. This concept has been further investigated in [8], where the selection of next-hop is performed by applying the findings of Multi-Attribute Decision Making theory. Although the aforementioned works propose strategies that prove to be powerful to contrast congestion events, they are all based on either

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extensions of TCP AIMD scheme or advanced routing schemes. In this regard, this paper aims at developing a congestion control mechanism for interplanetary networks, relying on both storage-routing schemes and next-hop MADM selection policies. In addition, also the implementation of advanced Random Early Detection (RED) and Explicit Congestion Notification (ECN) mechanisms within the delay tolerant network architecture is carried out.

The remainder of this paper is structured as follows. Section II shortly focuses on the delay tolerant network architecture, by paying attention on Custodial Transfer option and service differentiation schemes. Section III illustrates the essentials of the proposed solutions in terms of ECN and RED schemes for DTNs and MADM storage-based routing strategies. Performance analysis of the proposed solutions is presented in Section IV, whereas final remarks and conclusions are drawn in Section V.

II. Delay Tolerant Network (DTN) architecture

The Delay Tolerant Network architecture has been standardised within Internet Research Task Force (IRTF) and basically consists in the Bundle Protocol, which can implement store-and-forward operations, routing, retransmission of lost information blocks, and security extensions. The bundle protocol is commonly implemented beneath the application layer (where present) and over either transport, network or data link layer. Essentially, it encapsulates the messages coming from the application layer into Bundle Protocol Data Units (BPDUs), hereafter referred to as *bundles.* In turn, bundles are forwarded to the next-hop according to routing strategies (in fact not defined in [9]). Successful delivery of data is checked by means of delivery options set in the BPDU header and administrative records (i.e., notifications) generally issued by either DTN next-hop or destinations. In particular, the custodial transfer option deserves some attention. Basically, it allows electing some DTN nodes as custodians, which are responsible for retransmitting bundles missing at destination. In practice, the recovery phase is implemented as stop-and-wait ARQ (Automatic Retransmission request). Correct receipt of bundles is notified by means of administrative reports (i.e., positive acknowledgments, ACKs in the following). In case a bundle is not received, no positive acknowledgments are issued, resulting in bundle retransmission upon ACK timeout expiration. For further details about the other options available from the Bundle Protocol, the interested reader can refer to [10].

Service differentiation is performed as well by the bundle protocol. Three service classes are defined (*bulk*, *normal*, *expedited*) corresponding to different levels of priority that scheduling algorithms should take into account during routing operations. In more detail, "bulk" class include traffic flows with the least service requirements, whereas "expedited" is for data traffic demanding for the highest priority scheduling; "normal" implements intermediate priority.

Concerning the protocol layers underlying the Delay Tolerant Network architecture, this work assumes the Bundle Protocol to lie over the data link layer, implementing the Licklider Transmission Protocol (LTP) [11]. The physical layer implements the protocols specified by CCSDS, such as Telemetry, Telecommand and Proximity-1, whose choice depends on the characteristics of the transmission link (deep space or proximity).

III. The Integrated Framework

A. Congestion Control and Service Differentiation Issues

Future space networks are expected to integrate with terrestrial Internet and hence to handle data flows, characterised by different service requirements, expressed in terms of packet loss rate, throughput, delivery delay and jitter. In the case of interplanetary scenarios, this differentiation holds to some extent because data communications are affected by long propagation delays. Actually, in this context, it is more appealing to focus the attention on just reliability and speed of data transfer. In this perspective, it is possible to distinguish between data flows requiring either 1) the shortest delivery delay or 2) zero information loss probability. These two classes can be managed by the Bundle Protocol in terms of the priority classes therein implemented. In more detail, data flow requiring shortest delivery delay can be classified as "expedited". On the other hand, data flows with strict reliability constraints can be mapped to the "normal" class. Finally, the constraint of zero information loss probability can be matched by enabling the custodial transfer option on DTN nodes.

It is worth noting that the probability of congestion events occurring on DTN nodes, in terms of buffer overflow at the bundle protocol layers plays an important role here. Actually, unexpected buffer overruns may prevent specific service requirements from being respected. In more detail, two main considerations can be drawn. First, the last queued bundles will likely suffer from long waiting times before being forwarded to the next hop, thus experiencing very long delivery delays. Second, congestion events will result in possible buffer overflow, causing thereby bundle discard with a consequent non-negligible information loss probability. In order to cope with these performance impairments, adequate countermeasures need to be investigated. In case of small space network deployments, where data transmission is scheduled in advance, the use of static traffic control and shaping mechanisms can be considered. This work, instead, focuses on larger network configurations, where the adoption of static mechanisms could result ineffective. In this case, dynamic management of available resources and consequently of data transmission is needed instead. To this end, two mechanisms are proposed here and detailed as follows.

Firstly, the use of Random Early Detection (RED, [12]) at the bundle protocol layer is proposed and applied to for "normal" bundles. In fact, within each DTN node, incoming "normal" bundles are discarded with probability p_{RED}. This mechanism is enabled once the ratio between the number of queued normal bundles (Q_{normal}) and the difference between buffer capacity (Q_{MAX}) and the number of "expedited" bundles ($Q_{expedited}$) exceeds the admittance

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threshold RED_{thr}, which varies between 0 and 1. In more detail, if

$$\frac{Q_{normal}}{Q_{MAX} - Q_{expedited}} > RED_{thr} \tag{1}$$

the "normal" bundles are discarded with probability p_{RED}, which is a quantity increasing with the ratio reported in the first member of equation (1). In case of dropping event, the total number of refused "normal" bundles D_{normal} is increased accordingly.

Secondly, the use of Explicit Congestion Notification (ECN, [13]) is implemented at the bundle layer protocol and applied to "expedited" bundles. In practice, if the ratio between the number of queued "expedited" bundles and the difference between buffer capacity and the number of "normal" bundles exceeds the admittance threshold ECN_{thr}, varying between 0 and 1, an ECN flag implemented within the BPDU header is set to one. Finally, the number of marked bundles $M_{expedited}$ is increased accordingly. From the analytical viewpoint, if

$$\frac{Q_{expedited}}{Q_{MAX} - Q_{normal}} > ECN_{thr} \tag{2}$$

the "expedited" bundles are marked with probability p_{ECN}, which is a quantity increasing with the ratio reported in the first member of equation (2).

Finally, also an indicator of persistent congestion, *CP*, is introduced to track the congestion state of buffers. It is defined as sum of D_{normal} and $M_{expedited}$

B. MADM Storage-based Routing Scheme

Although implementation of RED and ECN schemes is beneficial to tackle congestion events, their adoption alone is not sufficient to effectively contrast persistent congestion events Hence, also advanced routing strategies aimed at preventing congestion events have to be considered. In this perspective, the advantages offered by storage-based routing seem attracting. Loosely speaking, the idea is to move the bundles stored in the DTN nodes that are about to experience congestion events to other DTN nodes, whose available buffer capacity is larger. As partially explored in [8], the selection of the next-hop is of fundamental importance to attain satisfactory performance levels, defined in terms of appropriate QoS metrics. This can be achieved by pursuing a Multi-Attribute Decision Making based approach [8], in order to deal effectively with performance metrics that can be in contrast one with another, such as power consumption and information loss rate (i.e., reducing the former results in an increase of the latter). In practice, decisions about the next-hop selection are performed hop-by-hop by Decision Maker (DM) entities, implemented within DTN nodes.

In the following, the next-hop selection criteria [8] are shortly revised for the sake of completeness. 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*. Let each $DM^{(n)}$ be characterised by a decision matrix: $X_{jk}^{n}(t)$ is the normalized value of the metric k measured at the time instant t for the node *n* when Next-Hop j is used. On the basis of the available measures, the decision makers will compute the most appropriate next-hop by applying specific algorithms. Here, the paper just focuses on two schemes, Simple Additive Weighting (**SAW**) and Technique for Order Preference by Similarity to Ideal Solution (**TOPSIS**), derived from the MADM theory.

As far as the former is concerned, the aim is to minimize the sum of all the attributes of interest. In practice, amongst all the possible J alternatives, the selection algorithm chooses the Next-Hop denoted as $j_{opt}^{n,SAW}(t)$, such as to minimize the sum of all attributes:

$$j_{opt}^{n,SAW}(t) = \left\{ j^{n} = \underset{j \in [1,J]}{\arg\min} \sum_{k=1}^{K} X_{jk}^{n} \right\} \tag{3}$$

As far the latter is concerned, the aim is to find the alternative that, from a geometrical point of view, is the closest to the *utopia point* (best alternative) and the farthest from the *nadir point* (worst alternative). In more detail, the vector of utopia points ${}^{id}X_{k}^{n}$ is defined as:

$${}^{id}X_{k}^{n} = \left\{ \begin{array}{l} X_{jk}^{n} : j = \underset{j \in [1,J]}{\arg\min} X_{jk}^{n}, \text{ for "cost" metrics} \\ X_{jk}^{n} : j = \underset{j \in [1,J]}{\arg\max} X_{jk}^{n}, \text{ for "benefit" metrics} \end{array} \right\} \tag{4}$$

On the other hand, the vector of nadir points ${}^{wr}X_{k}^{n}$ is defined as:

$${}^{wr}X_{k}^{n} = \left\{ \begin{array}{l} X_{jk}^{n} : j = \underset{j \in [1,J]}{\arg\max} X_{jk}^{n}, \text{ for "cost" metrics} \\ X_{jk}^{n} : j = \underset{j \in [1,J]}{\arg\min} X_{jk}^{n}, \text{ for "benefit" metrics} \end{array} \right\} \tag{5}$$

Hence, the TOPSIS algorithm chooses the Next-Hop called $j_{opt}^{n,TOPSIS}(t)$ amongst the J alternatives, by minimizing the so called *Similarity to Positive-Ideal Solution*:

$$j_{opt}^{n,TOPSIS}(t) = \left\{ j^{n} = \underset{j \in [1,J]}{\arg\min} \frac{S_{j}^{ng}}{S_{j}^{ps} + S_{j}^{ng}} \right\} \tag{6}$$

where S_{j}^{ps} and S_{j}^{ng} are the distances, in terms of Euclidean norm, between the alternatives and the utopia point (*Positive Separation*), and between the alternatives and the nadir point (*Negative Separation*), respectively.

C. The Proposed Solutions

The solutions proposed and tested (Section IV) in this paper actually combine the ECN and RED strategies, illustrated in Section IV-A, with storage-based routing

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strategies inherited from the MADM theory (Section IV-B). In this light, the design of possible solutions strictly depends on the choice of appropriate attributes. This work extends the range of attributes considered in [8], in order to take into account metrics that could also impact on ECN and RED performance. In more detail, the following measures have been taken into account: *i) Bundle Buffer Occupancy (BBO):* 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. *ii) Available Bandwidth (AB)*: the capacity in [bit/s] available on the links between node *n* and its neighbour *j*. As observed in the previous case: $AB_j^{(n)}(t) = X_{j2}^{(n)}$ but, here, it represents a "benefit" attribute. *iii) Transmission Time (TT)*: 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, the attribute is defined as $TT_j^{(n)}(t) = X_{j3}^{(n)}$, corresponding to a "cost" attribute. *iv) Bundle Buffer Occupancy Derivative (BBOD)*: the discrete derivative of the *Bundle Buffer Occupancy* for node *n*, at time instant *t*, notified from its neighbour *j*, defined as:

$$BBOD_j^{(n)}(t) = (BBOD_j^{(n)}(t) - BBOD_j^{(n)}(t-T))/T ,$$

where T is the length of the derivation window. In this case, $BBOD_j^{(n)}(t) = X_{j4}^{(n)}$, represents a "cost" attribute. This metric gives an indication on how fast the bundle buffer queue length varies with the time. *v) Congestion Persistence (CP)*: it is a measure of the congestion state of the bundle buffer at node *i*, notified from its neighbour *j*, at time instant *t*, defined as $CP_j^{(n)}(t) = D_{normal,j}^{(n)}(t) + M_{\exp edited,j}^{(n)}(t)$ (see section III-A). In this case, it yields $CP_j^{(n)}(t) = X_{j5}^{(n)}$ and it represents a "cost" attribute.

Hence, the proposed solutions use SAW and TOPSIS algorithms, applying the above-discussed metrics. For the simplicity of notations, the solutions will be referred hereafter to as SAW-"attributes" and TOPSIS-"attributes".

IV. Performance Analysis

A. Reference Scenario

The investigated environment is composed of two main portions: planetary (placed on the corners of Fig. 1) and backbone (centre of Fig. 1) regions. In more detail, on the one hand, each planetary region is composed of several planetary nodes (white circles) that can work as both traffic source and destination nodes.

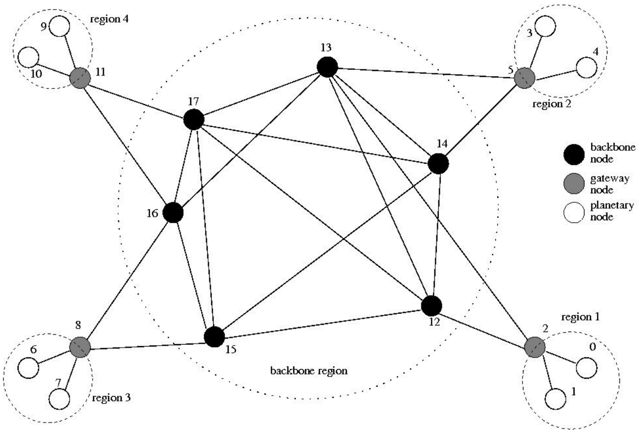

Fig. 1. The reference scenario

On the other hand, the backbone region is composed of several interplanetary nodes (black circles), serving as relay nodes, connected one with another through a mesh topology. Finally, the planetary regions are connected one with another through specialised gateway nodes (grey nodes), which are responsible for forwarding data towards destination through the backbone region. For the sake of exemplification, Fig. 1 reports the case of 4 planetary regions, composed of two planetary nodes. In particular, nodes 0, 9, and 10 are assumed as traffic source nodes, nodes 1, 4, and 6, as destination nodes, whereas nodes 3 and 7 can both transmit and receive data. Finally, nodes from 12 to 17 belong to the backbone region, whereas nodes 2, 5, 8, and 11 are gateway nodes.

B. Testbed Configuration

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 not strictly necessary.

Concerning the physical peculiarities of the considered network topology, 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 able to accommodate up 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.

TABLE I
BACKBONE REGION LINK CAPACITIES [KBIT/S]

Nodes	2	5	8	11	12	13	14	15	16	17
2	-	-	-	-	800	650	-	-	-	-
5	-	-	-	-	-	650	800	-	-	-
8	-	-	-	-	-	-	-	850	600	-
11	-	-	-	-	-	-	-	-	780	1000
12	800	-	-	-	-	700	700	100	-	400
13	650	650	-	-	700	-	400	-	400	400
14	-	800	-	-	700	400	-	250	-	350
15	-	-	850	-	100	-	250	-	200	150
16	-	-	600	780	-	400	-	200	-	80
17	-	-	-	1000	400	400	350	150	80	-

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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. The traffic sources have been set on the planetary regions. In particular, nodes 3, 7 and 9 send traffic flows with *Non Custodial Transfer* option (then classified as "expedited" traffic), whereas nodes 0 and 10 inject *Custodial Transfer* traffic (classified as "normal" traffic) into the network, in order to assess the robustness of the proposed MADM solutions. All the other planetary nodes are set as receivers. Table II reports the tested configurations, expressed as combination of the congestion control and link selection approaches proposed here. These will be hereafter referred to as *Mode*. The first column labels the Mode, the second reports the MADM optimization criterion (chosen between SAW and TOPSIS, defined in Section III-B), the third lists the attribute(s) considered in the multi-attribute optimization (formally described in Section III-C); the last column indicates whether RED and ECN strategies (introduced in Section III-A) are activate. In this case, thresholds $RED_{thr} = 0.7$ and $ECN_{thr} = 0.9$ are considered.

TABLE II
CONGESTION CONTROL AND LINK SELECTION CONFIGURATIONS

Mode	MADM Criterion	Employed Attribute(s)	Congestion Control
01	SAW	BBO	No
02	SAW	BBO	Yes
03	TOPSIS	BBO	Yes
04	SAW	BBO, BBOD	Yes
05	TOPSIS	BBO, BBOD	Yes
06	SAW	BBO, BBOD, CP	Yes
07	TOPSIS	BBO, BBOD, CP	Yes
08	SAW	BBO, CP	Yes
09	TOPSIS	BBO, CP	Yes
10	TOPSIS	BBO, AB, BBOD, CP	Yes
11	SAW	BBO, TT, BBOD, CP	Yes
12	TOPSIS	BBO, TT, BBOD, CP	Yes
13	TOPSIS	BBO, AB	Yes
14	SAW	BBO, TT	Yes
15	TOPSIS	BBO, TT	Yes

The performance of protocol solutions proposed in this paper has been carried out, by means of the *ns-2* simulator, properly adapted to the characteristics of the reference scenario, described above. A number of runs sufficient to obtain a width of the confidence interval less than 1% of the measured values for 95% of the cases is imposed, while a simulation time of 10000s was set for each test.

C. Results

The first part of results concerns the employment of the RED and ECN strategies. Figs. 2 and 3 report a comparison between the Mode 01, which does not use any congestion control mechanism, and Modes 02 and 03, which use the same attribute but apply different MADM criteria and, in particular, they activate the congestion control mechanisms. In more detail: Fig. 2 shows the *Bundle Loss Rate* (**BLR**), which is the ratio between the number of received and transmitted "expedited" bundles; Fig. 3 reports the *Number of Retransmission* (**NR**) of "normal" bundles.

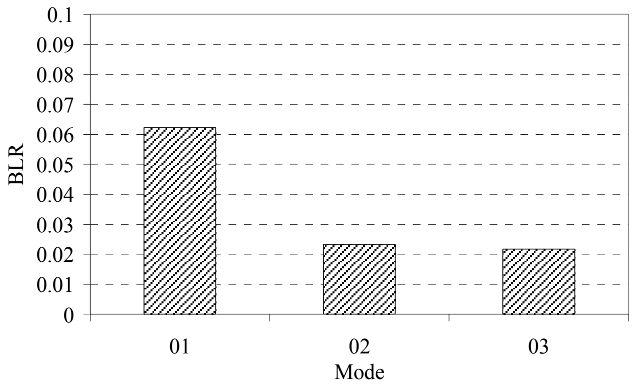

Fig. 2. **BLR** Comparison among Modes 01, 02 and 03

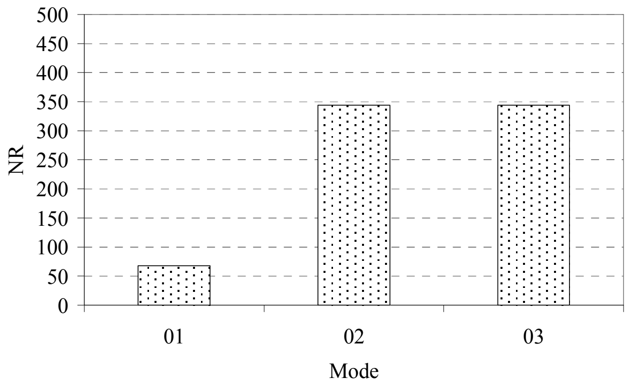

Fig. 3. **NR** Comparison among Modes 01, 02 and 03

When RED and ECN strategies are active, the reliability of the whole network improves: Modes 02 and 03 guarantee **BLR** around 2%. On the other hand, it is immediate to see that this performance gain is achieved at cost of large number of retransmissions (NR). In fact the joint effect of Custodial Transfer option and of the RED and ECN strategies leads to the increase of NR. This is mainly due to the fixed thresholds (RED_{thr} and ECN_{thr}), which imply a larger number of bundle to be discarded in the network nodes. If Mode 01 is used, the number of retransmissions increases to 68; when either Modes 02 or 03 are applied, NR raises up to 344. In practice, the performance improvement in terms of reliability and the more effective management of Bundle layer buffers result, qualitatively speaking, in higher power consumption because of the big number of bundles to be retransmitted.

The second part of results, reported in Figs. 4 and 5, concerns the comparison among combined congestion control and link selection approach, where the RED and ECN strategies have been implemented in all cases (Modes from 02 to 15). Two main aspects have been taken into account: the optimization criterion and the employed attributes. If the Modes are configured with similar attributes, the change of optimization criteria does not offer significant performance difference in terms of both **BLR** and **NR**. The crucial role is instead played by the specific attributes applied here. Regarding **BLR** (shown in Fig. 4), Modes 04, 05, 08 and 09 give the worst performance (**BLR** is around 8.5%). Similar considerations hold also for **NR** (Fig. 5).

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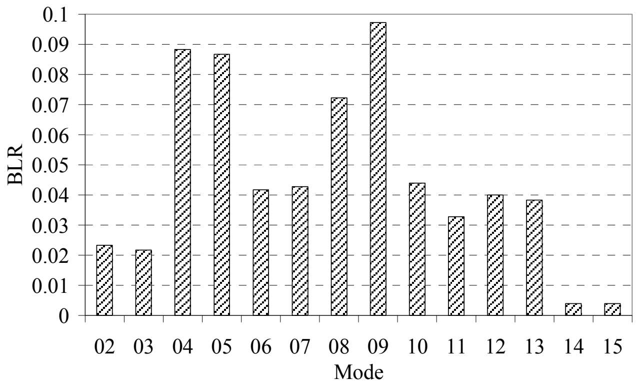

Fig. 4. **BLR** Comparison among Modes from 02 to 15

Intermediate performance (**BLR** about 4%) has been observed with Modes 06, 07, 10, 11, 12 and 13. As far as **NR** is concerned**,** the mentioned modes offer intermediate performance. By contrast, cases 12 and 13 show, in presence of the same **BLR** level, a significant number of retransmissions. This is mainly due to the TOPSIS approach, which privileges the attributes related to the bandwidth availability (*AB* and *TT*): the link selection process tends to frequently select the links with larger capacity, thus causing quick saturation of nodes' buffers.

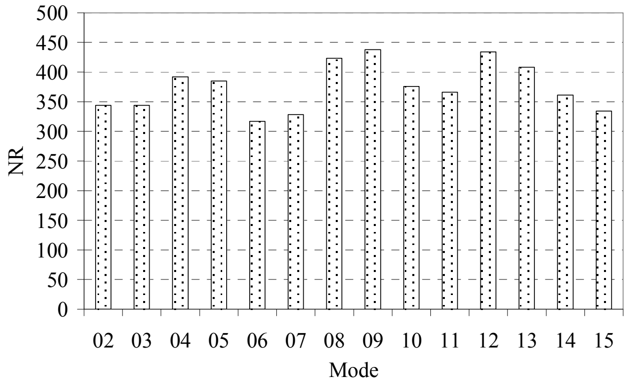

Fig. 5. **NR** Comparison among Modes from 02 to 15

Better performance is obtained with Modes 02, 03 (**BLR** is equal to 2%) and in particular 14 and 15 (where **BLR** is around 0.4%). In these cases, the low **BLR** levels imply smaller **NRs** and, as a consequence, lower energy consumption. In practice, the joint optimization of *BBO* and *TT*, without other attributes, combined with RED and ECN mechanisms allows attaining a really satisfactory performance.

V. CONCLUSIONS

This work focused on combined congestion control and link selection techniques applied to interplanetary networks. In more detail the effect of RED and ECN congestion control strategies have been associated with a MADM link selection approach. The performance analysis showed that the presence of congestion control significantly increases the interplanetary networks reliability and its use jointly with MADM solutions is really promising, in particular in terms of Bundle Loss Rate (**BLR**), when the *Bundle Buffer Occupancy* is simultaneously optimized with the *Transmission Time*.

REFERENCES

[1] K. Fall, "A delay-tolerant network architecture for challenged internets," ACM SIGCOMM 2003, Karlsruhe, Germany, Aug. 2003.

[2] Draft SIS-DTN Green Book, CCSDS, January 2009.

[3] B. Iannotta, "NASA Designs Internet-Style Deep Space Communications System," Space News, 1 December 2008.

[4] Ö. B. Akan, J. Fang, I. F. Akyildiz, "TP-Planet: A reliable transport protocol for interplanetary internet," IEEE Journal on Selected Areas in Communications, vol. 22, no. 2, Feb 2004, pp. 348-361.

[5] L. A. Grieco, S. Mascolo, "A congestion control algorithm for the deep space Internet," Space Communications, vol. 20, no. 3-4, 2005, pp. 155-160.

[6] S. Burleigh, E. Jennings and J. Schoolcraft, "Autonomous Congestion Control for an Interplanetary Internet," AIAA SpaceOps 2006 Conference, Rome, Italy, Jun. 2006.

[7] M. Seligman, K. Fall, P. Mundur, "Alternative custodians for congestion control in delay tolerant networks," ACM SIGCOMM 2006, Pisa, Italy, Sept. 2006.

[8] I. Bisio, T. de Cola, M. Marchese, "Congestion Aware Routing Strategies for DTN-based Interplanetary Networks," IEEE GLOBECOM 2008, New Orleans, LA, USA, Nov.-Dec. 2008.

[9] V. Cerf, S. Burleigh, A. Hook, L. Togerson, R. Durst, K. Scott, K. Fall, H. Weiss, "Delay Tolerant Networking Architecture," RFC 4838, Apr. 2007.

[10] K. Scott, S. Burleigh, "Bundle Protocol Specification," RFC 5050, Nov. 2007.

[11] S. Burleigh, M. Ramadas, S. Farrell, "Licklider Transmission Protocol - Motivation," IRTF Internet Draft, Jun. 2008.

[12] S. Floyd, V. Jacobson, "Random Early Detection Gateways for Congestion Avoidance," IEEE/ACM Transaction on Networking, vol. 1, no. 8, Aug. 1993, pp. 397-413.

[13] A. Kuzmanovic, "The Power of Explicit Congestion Notification," ACM SIGCOMM 2005, Philadelphia, PA, USA, Aug. 2005.