On the Design and Analysis of Fair Contact Plans in Predictable Delay-Tolerant Networks

Juan Andres Fraire, Pablo G. Madoery, and Jorge M. Finochietto

***Abstract*— Delay-tolerant networks (DTNs) have become a promising architecture for wireless sensor systems in challenged communication environments where traditional solutions based on persistent connectivity either fail or show serious weaknesses. As a result, different routing schemes have been investigated that take into account the time-evolving nature of the network topology. Among them, contact graph routing has been proposed for space environments with predictable connectivity. In order to evaluate routing decisions, DTN nodes need to know the contact plan in advance, which comprises all communication links among nodes that will be available in the future. Since not all potential contacts can belong to the contact plan, its design requires analyzing conflicting contacts in order to select those that meet an overall goal. In this paper, we consider the design of contact plans that can maximize fairness requirements while still maximizing the overall capacity as well. To this end, we propose to formalize the problem by means of an optimization model and evaluate its performance in terms of different fairness metrics. Since this model can be computationally intractable for a large number of contacts, we also propose to tackle it as a matching problem, resulting in algorithms of polynomial complexity, and compare these results with those of the original model. We show that fairness can be properly modeled to design contact plans and that efficient algorithms do exist to compute these plans quite accurately while also improving overall network routing metrics for a proposed case study.**

***Index Terms*— Delay tolerant network, topology design, link assignment, resource allocation, satellite constellations.**

I. Introduction

DELAY-TOLERANT Networks (DTNs) have received much attention during the last years as they have been proposed for several environments where communications can be challenged by either latency, bandwidth, errors, or stability issues [1]. Even if originally studied to develop an architecture for an Interplanetary Network (IPN) [2], DTNs have been recently recognized as an alternative solution for building future satellite applications [3]; in particular to cope with typical intermittent channels of LEO (Low Earth Orbit) sensor constellation systems [4].

Among the challenges to implement practical DTNs, the definition of a new communication protocol, which does not assume a persistent connectivity between the communication end points, has been addressed by the specification of the Bundle protocol [5], resulting in the availability of several software implementations of the protocol [6], [7]. Indeed, traditional protocols like TCP can not be used due to their conversational nature. Neither can traditional routing protocols be employed on environments with intermittent connections, where the network topology is time-varying. To this end, new routing mechanisms have been recently investigated [8]–[11]. In particular, if topology changes are predictable as in LEO environments [12], the Contact Graph Routing (CGR) [13] scheme is appealing as it takes advantage of the a priori knowledge of the *contact plan* between DTN nodes.

In general, a *contact* can be defined as the opportunity to establish a temporal communication link among two DTN nodes. However, it is possible that a given node may have more than one contact opportunity at a given time but limited or conflicting resources to only make use of one of these opportunities. As a result, the contact plan can be thought as a subset of the *contact topology* which comprises all contact opportunities a network of DTN nodes has over a given time window. The design of contact plans has received little attention, as it is either assumed that contact are scarce [2] or that all potential contacts between DTN nodes can belong to the contact plan [3]; in other words, that the contact plan equals the contact topology. Early works [15], [16] have focused on contact plans that can enhance the network connectivity for a given topology state, without taking into account the time-evolving nature of the contact topology. With the advent of DTNs, the design of contact plans that consider time-evolving topologies became relevant as it enables data traffic to traverse different topology states. Recent works [17], [18] have proposed the design of contact plans that can minimize path costs and maximize reliability; however, to the best of our knowledge fairness issues have not been addressed in the design of contact plans.

In this context, our goal is to model and compute proper contact plans that can provide equal opportunities to all DTN nodes for the purpose of exchanging data traffic. In this work, we extend our investigation of [19], where fairness is achieved over time by considering the time-evolving nature of the network topology as well as previous link assignments. To this end, we had formalized this problem by means of an optimization model, and then proposed computational efficient algorithms that can be used to design fair contact plans. Additionally, in this work, we analyse a particular case study of contact plan design for a distributed orbiting sensor network. Indeed, we evaluate the behaviour of the proposed models and algorithms by means of simulations encompassing realistic network traffic routed by CGR algorithm drawing important

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The authors are with the Digital Communications Research Laboratory, Universidad Nacional de Córdoba, Córdoba 5000, Argentina (e-mail: juanfraire@gmail.com; madoerypablo@gmail.com; jfinochietto@efn.uncor.edu).

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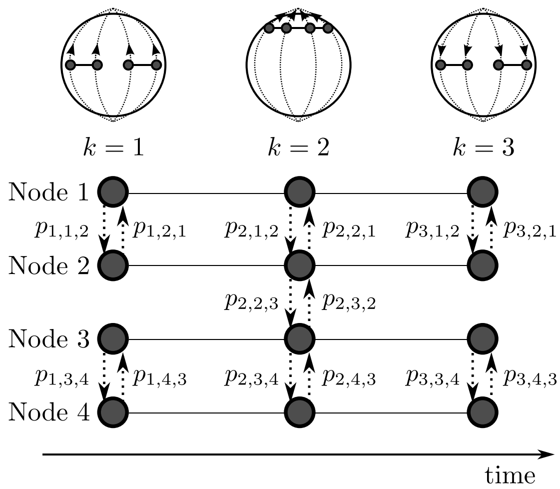

Fig. 1. Representation of evolving topologies: Contact Topology.

conclusions for the general contact plan design problem.

The paper is structured as follows. Section II describes the DTN model as a time-evolving topology where fairness can be implemented over time. The design problem is formalized in Section III as a multi-objective Mixed-Integer Linear Problem (MILP); while in Section IV, we model it as a matching problem and propose a novel algorithm to compute fair contact plans. Section V and VI evaluate and describe the performance of the different strategies in terms of fairness metrics in general and specific scenarios, respectively. Finally, Section VII concludes the work and discusses future directions.

II. System Model

We consider an Earth orbiting sensor constellation network without continuous end-to-end communication constraints as the model driver. As nodes in this network exhibit a concrete physical trajectory (i.e., orbits), communication links become sporadic but foreseeable. Particularly, since nodes position and attitude can be accurately estimated by precise analytic or numerical models, the communication opportunities (i.e. contacts) between them can also be predicted. To this end, one or more predefined link criteria (i.e. minimal range, Bit Error Rate, received signal power, etc.) must be satisfied so as to effectively declare a future contact as feasible. As a result, such constellations becomes predictable DTNs, where traffic flows over a predicted network topology in a *store-carry-and-forward* fashion before reaching its final destination.

In order to illustrate our system model, we analyse the example of an orbiting sensor network with 4 nodes as shown in Figure 1. Each node is equipped with transponders and antennas enabling cross-link over the equator and pole zones. The time-evolving nature of these links can be captured by means of graphs [20], capable of symbolizing links availability over time. For example, the physical proximity in the pole area might satisfy the link conditions allowing for more dense communication feasibility. This representation can be thought as a finite state machine (FSM) in which each state is described by a graph whose arcs (or edges), in turn, represent a feasible communication (i.e. contact) between network nodes (graph's vertex) during a given time. As a result, a combination of outgoing and incident directed edges in a given vertex represents a bidirectional (full or half-duplex) transponder, while a single directed edge a simplex transponder. In this work, we disregard simplex configurations and focus on full-duplex ones; nevertheless, the model can be extended to the former by properly affecting the associated link capacity.

Each state in the evolving graph can be identified by $k = 1, 2, \dots K$ conforming K graphs that comprise the same set of nodes but different edges among them. Particularly, in the suggested scenario, $K = 3$ states are required to delineate the communication link evolution during half an orbit time frame (i.e. from South to North pole). Therefore, the model considers several discrete communication scenarios (3 in the proposed example) obtained from a continuous satellite trajectory prediction. From a networking communication perspective such an abstraction results valid as long as the edges in the graphs are only enabled when the communication is guaranteed to be feasible (i.e. Bit Error Rate meets link requirements). Indeed, the model exhibit a state change (evolves to a new k) every time a contact starts or stops being viable as per the defined link criteria (each k state symbolize the network topology for a given t_k time). As a consequence, precise propagators and channel models (as in [21]) are mandatory so as to obtain a correct topology prediction for the contact plan design.

The aforementioned graph, illustrated with dotted edges in Figure 1, makes up a *contact topology* composed of $p_{k,i,j}$ links between node i and j at state k, where $p_{k,i,j}$ may adopt an integer identifier related to the communication interface. If no contact is feasible, then $p_{k,i,j} = 0$; while $p_{k,i,j} = a$ if the contact among i and j is possible via wireless interface a, where $a \geq 1$. For instance, we could state that $p_{1,1,2} = p_{1,2,1} = 1$ and $p_{2,2,3} = p_{2,3,2} = 2$, where $a = 1$ is associated to a short range transponder for links over the pole region, while $a = 2$, to a long range communication feasible on the equator zone. Besides, at state $k = 1$, $p_{1,2,3} = p_{1,3,2} = 0$ since no physical link exists between node 2 and 3. As a result, the contact topology can be defined by a three dimensional adjacency matrix $[P]_{k,i,j}$.

The contact topology assumes no resource limitation on the nodes; however, nodes may only be able to use a limited quantity of simultaneous links, even if more are potentially available. This can be due to power budget limitations, hardware design, interference requirements, among others. As a result, the maximum number of simultaneously active interfaces can be thought as a restriction to the contact topology $[P]_{k,i,j}$. The problem here lies in selecting the most appropriate set of possible contacts in a time-evolving graph with a certain criteria subject to interface usage restrictions or limitations. Consequently, we define an integer *interfaces* matrix $[I]_i$ constituted by the maximum i_i contacts a node i can simultaneously maintain at a given time. For example, if we assume $i_i = 1 \forall i$, and particularly for $i = 2$ in the case of Figure 1, a decision must be taken for node 2 and 3 at $k = 2$. Indeed, two possible solutions, as illustrated in Figure 2, are valid a) $p_{2,1,2}$, $p_{2,2,1}$, $p_{2,3,4}$, and $p_{2,4,3}$ or b) $p_{2,2,3}$ and $p_{2,3,2}$.

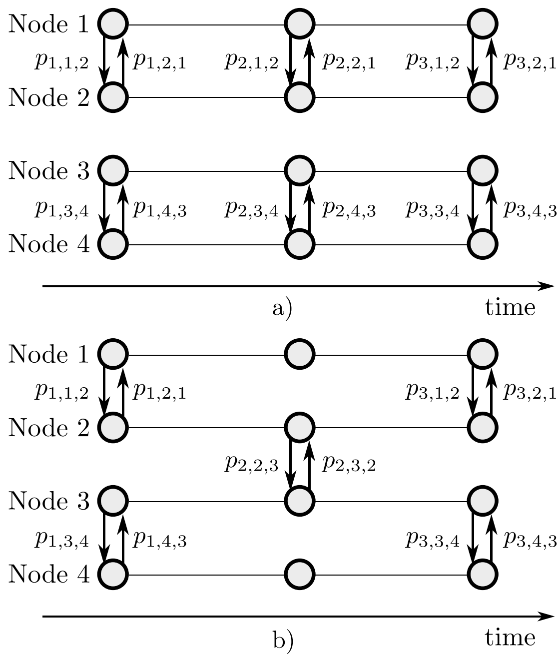

Fig. 2. Contact Plan for a) Maximum Capacity and b) Maximum Fairness.

Option a) delivers maximum total network capacity, while b) a fair and connected network by means of scheduling a contact between nodes 2 and 3.

In general, the described link selection can be defined as the *contact plan design problem*. The search of a general answer to the latter results not-trivial as nodes, edges, or states increases; becoming the principal motivation of the present work. Specifically, we focus on the exploration of an appropriate link selection method that maximizes the fairness in the resulting contact plan. The resulting plan is symbolized by $[L]_{k,i,j}$ whose $l_{k,i,j}$ elements represents the chosen unidirectional arcs from node i to j at state k. Therefore, enabled contacts in $[L]$ are in the same state in $[P]$ ($[L] \subseteq [P]$). Strictly speaking, $[P]$ stands for the potential contact set while $[L]$ is the concretion of $[P]$. Therefore, in a given contact design methodology, $[P]$ is provided as one of the inputs while $[L]$ is the expected output.

For the sake of simplicity, we assume communication links whose bandwidth is taken constant and equal for all nodes throughout the topology. This implies that link capacity is directly proportional to link connection time for all nodes. Therefore, in this work we aim at equalizing contacts global connection time; however, models and algorithms can easily be generalized to capacity units. On the other hand, we expect that a fair link allocation favours the flow of uniformly distributed traffic among the nodes, where all of them exchange traffic to all others. Indeed, we assume that, disregarding the routing method, a fair link distribution implies a fair distribution of the stated all-to-all traffic as well. We further analyse the impact of this assumption in Section VI-B.

III. Problem Formulation

In this context, our goal is to restrict by $[I]$ the contact topology represented in $[P]$ with the objective of maximizing the global system fairness in the resulting contact plan $[L]$.

TABLE I

Fairness Model Variables

Variable	Description
N	Number of nodes
K	Number of states
$[P]_{k,i,j}$	Set of $p_{k,i,j}$ contacts: contact topology
$[I]_i$	Set of i_i maximum simultaneous interfaces
$[T]_k$	Set of t_k time units for k state duration
$[L]_{k,i,j}$	Set of $l_{k,i,j}$ contacts: contact plan
t_{min}	Minimum assigned time to edge $\forall i, j, k$
t_{max}	Maximum assigned time to edge $\forall i, j, k$
t_{obj}	System capacity (time) in first iteration result
ϵ	Weight of system capacity in first iteration ($0 \leq \epsilon$)
β	Fraction of t_{obj} enforced in second iteration ($0 \leq \beta \leq 1$)

Among the many different definitions of fairness perhaps the most prevailing one is *min-max* fairness. In networking, a min-max fair link allocation is achieved when no further increase of any given link throughput is possible without decreasing the throughput of some other link with an equal or smaller allocation [22]. We base our model in this criteria as in [23], where on a first stage, the minimum edge capacity is maximized, and secondly, the maximum link capacity is minimized while keeping control of the overall network capacity obtained on the first stage. This assignment can be studied over the time-evolving network as described in Section II by means of a Multi-objective Mixed Integer Linear Programming (MILP) model with the variables detailed in Table I.

The first stage of the MILP problem can then be formulated as:

$$\text{maximize:} \quad t_{min} + \epsilon\left(\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} l_{k,i,j} * t_k\right) = t_{min} + \epsilon * t_{obj} \tag{1}$$

subject to:

$$\sum_{k=1}^{K} l_{k,i,j} * t_k \geq t_{min} \quad \forall i, j \tag{2}$$

$$l_{k,i,j} = l_{k,j,i} \quad \forall k, i, j \tag{3}$$

$$\sum_{j=1}^{N} l_{k,i,j} \leq i_i \quad \forall k, i \tag{4}$$

$$l_{k,i,j} \in \{0, 1\} \quad \forall k, i, j \tag{5}$$

Equation (3) restricts bi-directionality on the contact selection, thus, both reciprocal contacts or none of them can be selected. If a forward link deserves to be enabled, the same remains true for the return link to keep full or half-duplex channel configuration. Equation (4) is the main restriction to the topology as it limits the number of interfaces (links) to be enabled on each node i at any given state k. Finally, (5) applies a binary restriction for all $l_{k,i,j}$ variables, where 0 implies a disabled contact and 1 an enabled one. If $l_{k,i,j}$ results as active, it must take the $p_{k,i,j} = a$ value to represent the same interface as in $[P]$. Equation (2) bounds a real auxiliary variable t_{min} that stands for the minimum total time (capacity) a contact is enabled considering all k. Therefore, maximizing t_{min} entails enabling all contacts at least for t_{min}

time, obtaining an egalitarian link distribution among the nodes in the network. As fairness is improved, the network capacity is also maximized with the second term of (1) by means of an ϵ multiplier. It can be noticed that the higher ϵ, the more important the capacity respect to t_{min} (fairness). As a result, when $\epsilon \gg t_{min}$, the MILP model delivers the maximum capacity the system can offer under the specified restrictions without any fairness consideration. This yields a maximum capacity MILP reference model we will further consider in Section V under the name of MaxC_LP.

Up to this point, the objective of enabling contacts of less occurrence in the topology is satisfied by maximizing t_{min}, while the rest of the network links become enabled on a capacity maximization basis. Despite this provides certain min-max fairness, it can be further improved by re-distributing the resulting capacity (t_{obj}) with the aim of minimizing the usage of the arc with maximum capacity allocation measured by t_{max}. Such a furtherance in fairness can be modelled by a second stage of the MILP problem formulated as follows:

$$\text{minimize:} \quad t_{max} \tag{6}$$

subject to:

$$\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} l_{k,i,j} * t_k \geq t_{obj} * \beta \tag{7}$$

$$\sum_{k=1}^{K} l_{k,i,j} * t_k \leq t_{max} \quad \forall i, j \tag{8}$$

$$\sum_{k=1}^{K} l_{k,i,j} * t_k \geq t_{min} \quad \forall i, j \tag{9}$$

$$l_{k,i,j} = l_{k,j,i} \quad \forall k, i, j \tag{10}$$

$$\sum_{j=1}^{N} l_{k,i,j} \leq i_i \quad \forall k, i \tag{11}$$

$$l_{k,i,j} \in \{0, 1\} \quad \forall k, i, j \tag{12}$$

Restrictions (10), (11), and (12) remain as in (3), (4), and (5). In spite of the resemblance of (9) and (2), in (2), t_{min} is the variable to solve, while in (9) is a constant obtained from the first MILP iteration. Finally, equation (8) is now restricting the maximum contact allocation by t_{max}, implying that no i, j edge in the resulting $[L]$ topology can have a total capacity allocated higher than t_{max} throughout the k states of the contact plan. Moreover, restriction (7) forces the link selection up to a fraction β (satisfying $0 \leq \beta \leq 1$) of the maximum capacity t_{obj} obtained in the first MILP stage. Therefore, $(1 - \beta)$ can be interpreted as the capacity amount the system is allowed to forego in order to lower t_{max} (hence favouring the min-max fairness criteria). As a consequence, a $\beta < 1$ improves min-max fairness metric at the expense of penalizing network capacity. At the far end, a $\beta = 0$ would deliver a contact plan with all links enabled with the same minimum capacity (t_{min}), providing outstanding min-max fairness metrics, but in a scarcely connected network. Therefore, as our objective is to equally distribute the maximum capacity possible, we assume $\beta = 1$ for our modelling, naming this dual stage model as Fair_LP in the following sections.

The contact plan design problem with multiple objectives and linear restrictions as just formulated are a special case of linear programming with binary unknown variables which are known to be NP-complete. Solving the problem in this way quickly becomes computationally intractable as the addition of nodes, contacts, or states exponentially increases the required resolution time. In Section IV we propose an algorithmic alternative that provides a sub-optimal solution under polynomial complexity.

IV. Algorithmic Approach

If the contact plan is limited to the fact that each node can only implement *one contact at a time*, the design of the contact plan can also be investigated as a matching problem, which has to be solved at every state. In our context, a matching consists of a set of contacts such that no node is assigned more than one contact in a given state. Since each state can be associated to a general graph, we need to consider the general matching problem which can be solved by means of the Blossom algorithm [24], [25]. Besides, since our goal is to provide fairness over time, contacts (i.e., edges) can be weighted as a function of the time a pair of nodes has not been assigned a link between them. As a result, given a general graph, the algorithm finds a maximum edge number matching such that each vertex is incident with at most one arc in the matching. In particular, given a topology matrix $[P]$, Blossom finds $[L]$ with a sub-set of maximum edges restricted to one interface per node (i.e $[I]_i = 1 \forall i$) for a given k.

In Blossom, the matching is constructed by iteratively improving an initial empty matching along augmenting paths in the graph. At each iteration the algorithm either finds an augmenting path, finds a *blossom* (cycles of edges) and recurses onto the corresponding contracted graph, or concludes there are no augmenting paths. If there were no cycles, the algorithm reduces to standard bipartite matching. The interested reader can refer to [24] and [25] for an extended description of Blossom algorithm.

The Blossom algorithm only search for perfect matchings (also known as 1-factor or complete matching), this is, covering all vertex. However, our problem pursues the maximum weight in the more general case of, not necessarily perfect, maximum matching (i.e. we are willing to leave an uncovered vertex as long as the sum of weights is maximized). In [26] a reduction of the maximum (non-perfect) matching to a perfect matching problem is proposed. This reduction doubles the size of the graph and includes as many auxiliary edges as nodes in the main graph. The Blossom solution over the reduced graph satisfies the need for a single-interface restricted fair contact plan design algorithm further described in Section IV-A.

A. FCP-DTN Algorithm

The proposed fairness algorithm takes the contact topology $[P]$ as input and provides a contact plan $[L]$ as result. With a dynamic programming approach, the inner calculation aims for maximizing the minimum and minimizing the maximum arc selection by applying the reduced Blossom algorithm to $[P]$ with contact weights updated on a per state basis. We name

Algorithm 1: FCP-DTN Algorithm

input : Contact Topology $[P]$ of size $K \times N \times N$
State Time $[T]_k$
output: Contact Plan $[L]$ of size $K \times N \times N$

1 $DCT_{i,j} \longleftarrow 0 \quad \forall i, j$;
2 **for** $k \leftarrow 0$ ***to*** K **do**
3 $\quad [W]_{k,i,j} \longleftarrow DCT_{i,j} \quad \forall i, j$
4 $\quad$ `Blossom(`$[P]_k$,$[L]_k$,$[W]_k$`);`
5 $\quad$ **if** $[L]_{k,i,j} = 0$ **then**
6 $\quad\quad DCT_{i,j} \longleftarrow DCT_{i,j} + t_k \quad \forall i, j$

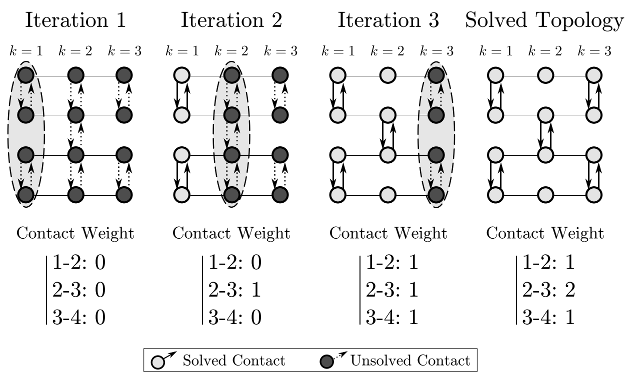

Fig. 3. FCP-DTN algorithm behavior with example topology.

the procedure FCP-DTN (Fair Contact Plan for Delay-Tolerant Network) or simply FCP, and illustrate its steps in Algorithm 1.

Throughout K iterations, the FCP algorithm keeps track of the amount of time a given contact has remained inactive (either by physical infeasibility or previous FCP decisions) in *Disabled Contact Time* (DCT), which is initialized to 0 in line 1. At each iteration, edge weights $[W]$ are calculated based on the accumulated DCT ($DCT_{i,j} = t_{k1} + t_{k2} + \cdots + t_{kn}$) for each arc i, j in line 3. As a consequence, the more time a link is not in the resulting contact plan $[L]$, the more weight it gets, and the more chance it has to be chosen in future states. Blossom algorithm with the proper maximum matching reduction is included as a sub-routine for such a selection in line 4. Finally, $DCT_{i,j}$ is updated in line 6 as per the decisions taken by Blossom algorithm in the current iteration. The FCT algorithm completes after iterating through all K states of the topology. Figure 3 graphically illustrates the iterations of the algorithm if executed over the example topology given in Section II. It can be observed that the FCP solution topology is equal to the maximum fairness selection of Figure 2 b).

Regarding overall complexity, several efficient implementations such as [27] solves Blossom algorithm in $O(n^2 l)$, where n is the node number and l is the edge quantity. Considering that we aim at finding a maximum non-perfect matching, the reduction to the graph increases Blossom routine complexity to $O(2n^2(2l+n))$. Finally, as the FCP algorithm iterates through all k states of the topology model, it can be demonstrated that the final FCP complexity becomes $O(2kn^2(2l+n))$.

Last but not least, the dynamic programming nature of the algorithm allows not only to distribute contacts equitably among the nodes but also in time through the designed contact plan. This is probably the most interesting feature of FCP as it not only provides a fair edge distribution but a direct improvement on the behaviour of real routed traffic in the resulting contact plan. The analysis of the latter is the main extension to our previous work in [19] further described in Section VI-B.

V. Performance Evaluation

A. Evaluation Metrics

In order to quantify the properties of contact plans delivered by the MILP models and FCP algorithm, we propose the following capacity and fairness metrics:

- Arc Contact Time:

$$arcConT_{i,j} = \sum_k l_{k,i,j} * t_k$$

- System Contact Time:

$$sysConT = \sum_k \sum_i \sum_j l_{k,i,j} * t_k$$

- Min-Max Fairness Index:

$$minMaxTRatio = \frac{min_{i,j}(\sum_k l_{k,i,j} * t_k)}{max_{i,j}(\sum_k l_{k,i,j} * t_k)}$$

- Raj-Jain Fairness Index [28]:

$$JIndexRatio = \frac{(\sum_i \sum_j \sum_k l_{k,i,j} * t_k)^2}{(i * j) * \sum_i \sum_j (\sum_k l_{k,i,j} * t_k)^2}$$

The *Arc Contact time* metric provides a direct measure of the total time a given contact i, j is chosen to be enabled throughout the final contact plan ($[L]$). The sum of these times for all contacts results in the *Total System Contact* time. Therefore, these measurements quantify the capacity a given pair of nodes share in the contact plan and the total network capacity respectively.

In addition to capacity metrics, *Min-Max Fairness Index* compares the most deprived and most benefited edges in the resulting contact plan. The latter is the optimization criteria driving the linear programming modelling. Nevertheless, since this metric only acknowledges extreme values neglecting the distribution of the remaining edges, we suggest *Raj-Jain Fairness Index* [28] as an auxiliary yet valuable fairness metric for reference.

B. Model and Algorithm Evaluation

For evaluation purposes, we suggest a test topology characterized by $K = 30$ states with 10 time units per state, $N = 10$ nodes, and 30% link density. Link density stands for the chance a set of uniformly distributed random contacts has to exists in the original contact topology $[P]$.

TABLE II
TEST TOPOLOGY METRICS

	Fair_LP Model	FCP-DTN	MaxC_LP Model
sysConT	2640	2640	2640
minMaxTRatio	0.5	0.25	0
Jain Index	0.841	0.825	0.731

As stated in Section III, fairness model (Fair_LP) parameters ϵ and β are set to 0.1 and 1 respectively, implying that the minimum arc contact time (t_{min}) must be maximized despite capacity penalty in the first iteration of the MILP resolution, and that no capacity must be resigned in the second stage distribution. We expect this model to deliver the fairest (in terms of min-max) contact plan. On the other hand, the capacity model (MaxC_LP) is also considered part of the analysis as it is a valid reference for the contact plan with maximal $sysConT$. Indeed, it allows to measure the capacity penalty incurred in the attempt of achieving fairness in the Fair_LP and FCP contact plans. As also stated in Section III, the MaxC_LP model is a particular case of the fairness MILP where $\epsilon \gg t_{min}$. Most importantly, our third method to evaluate is the FCP-DTN algorithm, whose specifications remain as described in Section IV.

Considering the suggested scenario, an intuitive visualization of the models and algorithm decisions can be illustrated through histograms where all possible i, j contacts are ordered in the abscissa axis, and the corresponding contact time or capacity ($arcConT_{i,j}$) in the coordinates axis. With the purpose of exhibiting the degree of equity in the distribution, the i, j arcs are sorted by their respective original un-restricted (physical) capacity in the contact topology $[P]$. For comparison we plot the Fair_LP model, the MaxC_LP model, and the total physical capacity of the arc (PhyC) against FCP-DTN. The histograms are illustrated in Figure 4 and the metrics summarized in Table II.

Even with the uneven physical distribution suggested by the slope in the PhyC values, both Fair_LP model and FCP-DTN equitably administer capacity to each of the contacts. In particular, contacts with less potential capacity (towards the right of the histogram) get prioritized treatment achieving as much connection time as physically possible (t_{min}). As expected, such a phenomenon is not observed in the MaxC_LP model case, whose assignments tend to be proportionate to the physical capabilities resulting in higher chance of deprived arcs in the provided contact plan. A clear example of the latter is the case of arcs (4, 8) and (0, 8) both with zero final capacity in MaxC_LP, but 20 and 10 in FCP-DTN and 20 and 20 in Fair_LP Model. As a consequence of a 0 capacity link in the MaxC_LP model, its $minMaxTRatio$ results in $min_{i,j}(\sum_k l_{k,i,j} * t_k) = 0$ as can be seen in Table II.

It is interesting to note, that despite the fairness metrics improve in both Fair_LP and FCP-DTN results, they account for the maximum system capacity ($sysConT$). This suggests that, for this topology, several solutions can yield a total of 2640 global capacity, among which the optimal min-max fairness contact plan is chosen by Fair_LP, and a near optimal is delivered by FCP. Notwithstanding, we prove below that in average, capacity loss is observed in Fair_LP when necessary for maximizing t_{min} value.

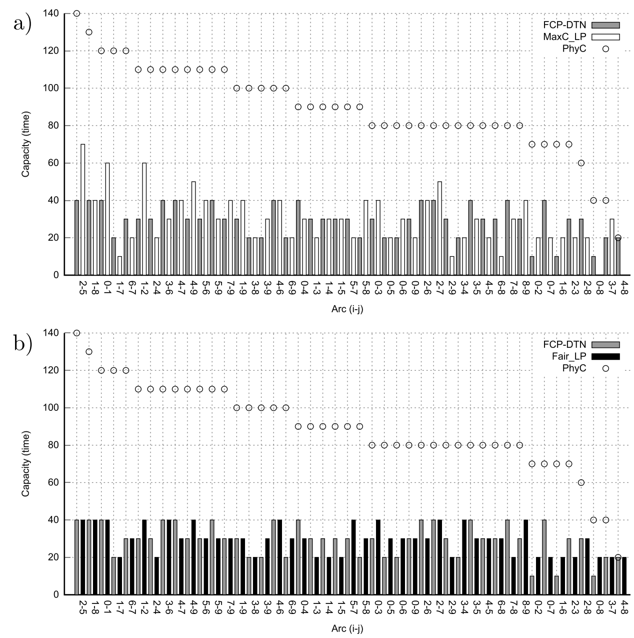

Fig. 4. Test Topology Arc Capacity Distribution for FCP-DTN vs a) MaxC_LP, and b) Fair_LP.

As a more general analysis of the methods proposed, we evaluated the algorithm and models in different and random topologies with varying contact densities. Particularly, 10000 simulated contact topologies $[P]$ were generated with uniform link existence probabilities ranging from 6% to 24% for $K = 30$ states and $N = 10$ nodes. Such ranges were chosen as they allow MILP models to be solved in reasonable time frames. Contact densities higher than 30% quickly become computationally intractable with most available MILP solvers. FCP on the other hand, with a polynomial complexity bound, does not evidence such restriction.

Resulting analysis metrics are illustrated in Figure 5 and considered hereafter. In a), system capacity curve illustrates the general behaviour of the test topology $sysConT$ metric aforementioned in Table II. FCP-DTN provides optimal capacity (equal as MaxC model) in contrast to fairness MILP model. This is consequence of the first stage of the Fair_LP MILP model which attempts to maximize t_{min} disregarding any capacity penalty implied; whereas FCP chooses, on a per state basis, the most fair arc combination that satisfies a maximum weight matching (driven by Blossom). Therefore, FCP keeps capacity optimal as far as no edge weights more than the sum of its competitors in the same k state, which is an unlikely situation in a uniformly distributed random arc scenario. Strictly speaking, FCP algorithm, as stated, takes less drastic fairness decisions than the MILP model, but delivering better overall network capacity. Supporting the former hypothesis, Figure 5 b) and c) demonstrates that FCP-DTN provides fairness metrics in between the Fair_LP and the MaxC_LP MILP models for all the generated random scenarios.

Concluding the evaluation, FCP has proven to deliver a promising balance of fairness and overall capacity of particular interest for the contact plan design for time-evolving delay

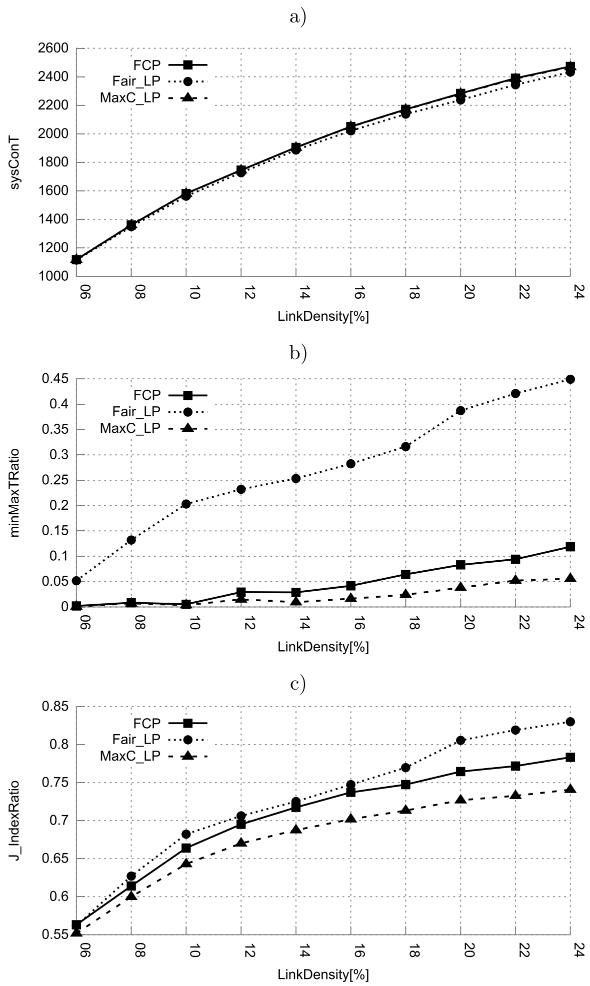

Fig. 5. Metrics for a) System Capacity, b) Min-Max, and c) Jain Index Ratio.

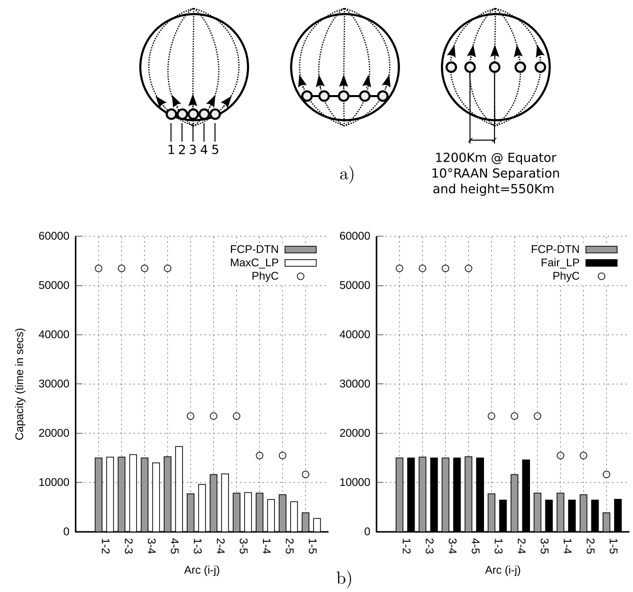

Fig. 6. a) Topology Diagram, b) Topology Arc Distribution.

TABLE III
CASE STUDY TOPOLOGY METRICS

	Fair_LP Model	FCP-DTN	MaxC_LP Model
A.Bundle Age [s]	43000	41000	44500

tolerant networks. We further deepen on this attribute in a particular case study in Section VI.

VI. CASE STUDY: LINEAR SENSOR FORMATION

A. Contact Plan Design

Early works have focused on developing efficient orbiting satellites topologies aiming at providing simultaneous global coverage [29] for end-to-end voice services (i.e. non-delay tolerant networks). However, this remains an open research topic for sensor based DTNs, where the term *efficient topology* requires to be redefined since end-to-end connectivity is no longer a network property. Furthermore, efficiency is also related to the constellation's mission, which determines the specific topology design criteria [30]. In this context, and in order to evaluate how the FCP algorithm can support real constellation planning, we propose an equator-parallel line flight formation topology as case study, where the wireless sensor constellation foot-print is particularly appealing for wide-coverage earth observation missions. As shown in Figure 6 a), this topology is characterized by frequent all-to-all link possibilities near the poles while scarce or none at all in the equator zone.

Specifically, we study an scenario with a 5 nodes constellation describing a 90° orbit inclination and slightly different mean anomalies (0°, 0.1°, 0.2°,0.3°, and 0.4°) to avoid collisions in the pole. A mean motion of 15.0756 revolutions per day and 0 eccentricity provides a semi-major axis of $6921km$ (i.e. a $550km$ perigee height) for the satellites low-Earth orbits (LEO). An orbit plane separation of 10° is achieved by varying the right ascension of the ascending node (RAAN) by the specified amount, yielding an inter-satellite separation of $1220km$ at the equator. Furthermore, for the sake of simplicity, we assume a $1000km$ maximum communication distance with omni-directional antennas as a link feasibility condition. Also, we used the publicly available simplified general perturbations (SGP4) propagation algorithm to provide the nodes position for $24h$ with $1s$ of accuracy. Further processing of the trajectory and the link condition rendered the corresponding $[P]_{k,i,j}$ contact topology to feed the models and algorithms. It is interesting to note that the contact topology derived from more than a day of 5 LEO nodes trajectory drives the MILP model unsolvable in reasonable time.

As many states represent considerable time lapses in the resulting contact topology $[P]_{k,i,j}$, special consideration must be taken as both models and algorithm fairness decisions are taken on a per-state basis. In other words, given a k state representing t_k time, where t_k is considerably large, a state fractionation provides better decision granularity, therefore, a fairer link assignment possibility. As a consequence, we fractionate the resulting topology for states with times larger than $t_k >= 500s$.

Metrics recorded from the contact plans designed by MaxC_LP, Fair_LP, and FCP are summarized in Table III. In general, the hypothesis raised from the random topology evaluation in Section V remains valid as the FCP system connection time $sysConT$ results optimal, and the $minMaxTRatio$ lies in between the MaxC_LP and Fair_LP models metrics. The phenomenon of a Jain's Index ratio ($JIndexRatio$) with slightly better performance in FCP-DTN than Fair_LP needs of Figure 6 b) histograms for further explanation. FCP assigns part of the most deprived arc capacity (edge $(1, 5)$) to others contacts in a distributed fashion improving the general quadratic mean distance ($JIndexRatio$). However, this reduce the capacity of the most unprivileged contact directly impacting on FCP $minMaxTRatio$ metric. Indeed, a trade-off from $minMaxTRatio$ to $JIndexRatio$ exists between Fair_LP and FCP. At this point, it is interesting to observe that arc $(1, 5)$ is a unique and scarce direct transmission opportunity for nodes 1 and 5 over the pole. As a consequence, when considering not only lowest and highest links capacities but also intermediate ones (as $JIndexRatio$ does), FCP delivered a contact plan with a more homogeneous capacity distribution than Fair_LP, which is only driven by a min-max criterion.

B. Simulation Results

We further evaluate the design of contact plans bringing them under real route calculation by means of simulation. An OMNeT++ framework based protocol and routing simulator was developed encompassing generic channel and data link models, and a Bundle protocol [5] model including CGR [13] algorithm for distributed routing on the flight sensor nodes. The interested reader can find similar simulations with CGR in [12] and [14]. The contact plans designed in previous Section VI-A are provided as input to the simulator. Our goal is to study the average time a *bundle* (Bundle protocol data unit) takes to reach its destination on each contact plan under an all-to-all traffic scenario. The metric we expect from the simulation is the *average bundle age*, which is the time lapse between bundle generation time (at the beginning of the simulation) until it arrives at the destination node.

In particular, we are varying the generation of data in each flight sensor from 4 to $7.6MBytes$ equally distributed to all feasible destinations, namely, 1 to $1.9MBytes$ to each of the four neighbours in the sensor network. Also, a second simulation with $10MBytes$ was considered to evaluate system saturation point. The traffic is generated at the beginning of the simulation and is evacuated in a *store-carry-and-forward* fashion as the time advances towards the $24h$ which is the duration of the designed contact plans. All links are configured as full-duplex with a data-rate of $10Kbps$, a 2 seconds acquisition and synchronization penalty per contact, a data link layer overhead of $12Bytes$ for a $2043Bytes$ payload (*bundle*) length and no reception acknowledgement. These parameters closely resemble expedited service of a point to point inter-satellite link (ISL) configuration of the CCSDS Proximity-1 Data Link protocol [31]. No bit error rate calculation of the channel is enabled in order to focus our analysis on the Bundle layer.

The plot in Figure 7 depicts the average bundle age, for different all-to-all traffic volume and for each contact plan designed with MaxC_LP, Fair_LP, and FCP-DTN algorithm. It is interesting to note how FCP algorithm delivers a contact plan capable for the lowest $AverageBundleAge$ in the network, outperforming Fair_LP, and MaxC_LP for all the traffic values simulated. The same holds true in network saturation point, achieved as data reaches $8MBytes$, deriving in the results summarized in Table IV. Saturation bundle ages remains constant as traffic grows since network is performing under full capacity and the metric is taken for bundles that effectively reach their destination (non-delivered bundles are not accounted).

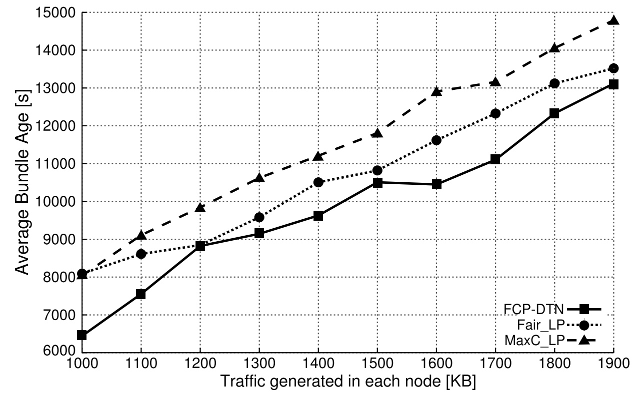

Fig. 7. Average Bundle age as the traffic in the network increases.

TABLE IV
AVERAGE BUNDLE AGE ON NETWORK SATURATION POINT

	Fair_LP Model	FCP-DTN	MaxC_LP Model
A.Bundle Age [s]	43000	41000	44500

Topological model evaluation from Section V supports the exposed improvement of $AverageBundleAge$ metric in Fair_LP with respect to MaxC_LP model; however, the fact that FCP outperforms both of them requires further analysis. This is consequence of the static formalization of the MILP models, in contrast to the dynamic-programming paradigm of the FCP algorithm. In other words, Fair_LP would still consider the allocation of contacts in consecutive k states as fair, while FCP solves the topology on a state by state basis, fairly distributing the links as k evolves (Fig. 3). Indeed, this feature leads to a topology with improved all-to-all route delays throughout the contact plan.

In this case study, we implemented the designed plans in a particular routed network in order to further analyse the assumption that a *fair link distribution implies a fair distribution of an all-to-all traffic* stated in Section II. We proved that FCP dynamic-programming methodology is of particular value for the design of contact plans for real routed delay tolerant sensor networks.

VII. CONCLUSION

In this paper we have investigated the design of fair contact plans for predictable delay tolerant sensor networks, in particular, for orbiting constellations. By finding a general design methodology, we have contributed to the planning of link utilization under restrictions on the number of simultaneous communications links a node can support at a given time.

Despite the formal statement in terms of linear programming allows to study optimal solution boundaries, they proved to be of little practical use as they lead to unacceptable computational complexity. This inspired FCP, an algorithmic approach capable of offering a balanced link assignment. Our investigation proved that FCP, under several general scenarios, provided optimal capacity while improving fairness metrics. Moreover, by means of a specific case study, FCP proved to be of significant support for planning routed networked constellations with all-to-all traffic patterns.

As one of the first research in the area, we focused our analysis on the specificity of a single interface restriction. Relaxing the interface uniqueness turns FCP algorithm useless requiring a different, probably heuristic, approach. We leave such a research as further work. On the other hand, our case study analysis pointed to a very interesting research topic: the design and optimization of more specific contact plans that considers the *a-priori* knowledge of the network traffic and routing scheme.

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Juan Andres Fraire received the Telecommunications Engineering degree from the Instituto Universitario Aeronáutico, Córdoba, Argentina. He is currently pursuing the Ph.D. degree in engineering sciences with the National University of Córdoba, Córdoba, as a member of the Digital Communications Laboratory. His main focus of research is predictable delay and disruption tolerant networking topology design and planning for space-oriented applications. He is currently a Communications Protocol Architect with Servicios Tecnológicos Integrados Company, San Carlos de Bariloche, Argentina, where he is currently developing DTN solutions for earth-observation LEO constellations projects defined in the Argentinean Space Agency (CONAE) National Space Plan.

Pablo G. Madoery received the Telecommunications Engineering degree from the Instituto Universitario Aeronáutico, Córdoba, Argentina, in 2012. He was with the Digital Communication Laboratory, National University of Córdoba, Córdoba, where he was involved in the field of satellite communications, and currently pursuing the Ph.D. degree in engineering sciences with a focus on the models, algorithms, and protocols for predictable delay and disruption tolerant networks.

Jorge M. Finochietto received the M.S. and Ph.D. degrees in electronics engineering from the Universidad Nacional de Mar del Plata, Mar del Plata, Argentina, and the Politecnico di Torino, Turin, Italy, respectively. His research interests are in the field of performance evaluation, high-speed networking and switching, and optical and wireless networks. He is currently an Associate Professor with the Universidad Nacional de Córdoba (UNC), Córdoba, Argentina, and an Adjunct Researcher with the National Research Council of Argentina. From 2005 to 2007, he was a Post-Doctoral Student with the Telecommunication Network Group, Politecnico di Torino. Since 2007, he has been a member of the Digital Communications Group at UNC. He has been involved in several national and international research projects in the field of communication networks. He has co-authored over 50 papers published in international journals and presented in leading international conferences.