On the Resource Efficiency of Virtual Concatenation in Next-Generation SDH Networks

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Abstract—Virtual concatenation (VCAT) is an SDH/SONET network functionality recently standardized by the ITU-T. VCAT provides the flexibility required to efficiently allocate network resources to Ethernet, Fiber Channel, ESCON and other important data traffic signals. The aim of this paper is to quantify the savings in network resources provided by VCAT, with respect to contiguous concatenation (CCAT), in SDH/SONET mesh transport networks bearing protected Scheduled Connection Demands (SCDs). We define mathematical models to quantify the add/drop and transmission resources required to instantiate a set of protected SCDs in either a VCAT-capable or a CCAT-capable network. Quantification of transmission resources requires a Routing and Slot Assignment (RSA) problem to be solved. We formulate the RSA problem in VCAT- and CCAT-capable networks as two different combinatorial optimization problems: RSAv and RSC, respectively. Protection of the SCDs is considered in the formulations using a Shared Backup Path Protection (SBPP) technique. We propose a Simulated Annealing (SA) based meta-heuristic algorithm to compute approximate solutions to these problems (i.e., solutions whose cost is close to the cost of the optimal ones). The gain in transmission resources and the cost structure of add/drop resources making VCAT-capable networks more economical are analyzed for different realistic traffic types (ESCON, GbE, Fibre Channel, voice).

I. INTRODUCTION

The ANSI SONET and ITU-T SDH standards of the mid-80’s aimed at developing standard-based interoperable transport networks. The main client of these networks was the telephonic traffic in the form of DSx (USA) and Ex (Europe) PDH signals [1]. Multiplexing hierarchies were defined to create SDH/SONET connections whose payload rates matched those of the DSx and Ex signals. Thus, a fundamental High Order (HO) SDH connection was defined as a bearer channel for E4 signals of 139.264 Mbps. Such an HO connection, based on an STM-I (Synchronous Transport Module) Time Division Multiplexing (TDM) frame structure, is typically referred to as a VC-4 connection and has a line rate (payload + overhead rate) of 155.52 Mbps. A multiplexing mechanism called contiguous concatenation (hereafter referred to as CCAT) was defined to create HO connections whose rates are multiples of the VC-4 rate. In particular, VC-4-4c, VC-4-16c, VC-4-64c and more recently VC-4-256c connections, with line rates of 622.08 Mbps, 2488.32 Mbps, 9953.28 Mbps and 38486.01 Mbps, respectively, were defined.

The massive adoption of computer applications, mainly fueled by the popularity of the Internet, significantly increased the volume of computer-generated data traffic. Interim proprietary mechanisms such as Packet over SONET (PoS) were developed to map data traffic onto SDH connections. These solutions were, however, unsatisfactory with respect to resource efficiency because of the mismatch between the nominal rate of popular data networking technologies such as Ethernet (10 Mbps), Fast Ethernet (FE, 100 Mbps), Gigabit Ethernet (GbE, 1000 Mbps), Enterprise System Connection (ESCON, 200 Mbps) and Fiber Channel (FC, 1000 Mbps) on one hand, and the payload rate of VC-4-Xc connections on the other hand. For example, a Fast Ethernet signal has to be born on a VC-4 connection, using only about 67 % of the VC-4’s payload.

Projects under the Data Aware initiative of the ANSI and the ITU-T led to a set of recommendations aimed at the development of SDH/SONET networks versatile and suitable for the transport of data traffic. The recommendations define a Generic Framing Procedure (GFP) to map different types of data networking signals onto SDH/SONET connections. GFPs were developed to map data traffic onto SDH connections. An HO connection, based on an STM-I (Synchronous Transport Module) Time Division Multiplexing (TDM) frame structure, is typically referred to as a VC-4-Xv connection to be dynamically updated without service disruption. VC-4-Xv connections can be defined to closely match the nominal rate of a particular signal. For example, 7 VC-4s can be virtually concatenated to form a VC-4-7v connection of about 1050 Mbps to bear a GbE signal. In this study we assess the gain in network resources provided by VCAT with respect to CCAT.

We consider a form of traffic called Scheduled Connection Demands (SCDs). An SCD is a connection demand represented by a tuple \((s, d, n, \alpha, \omega)\) where \(s\) and \(d\) are the source and destination nodes of the connections, \(n\) is the number of requested VC-4 connections and \(\alpha, \omega\) are the set-up and tear-down dates are known in advance.

1As explained later, a Scheduled Connection Demand (SCD) is a connection demand for which the set-up and tear-down dates are known in advance.
down dates of the connections. Table I shows an example of a set of SCDs. Scheduled connections correspond, for example, to SDH Soft Permanent Connections (SPCs)\(^2\) requested by a company from a service provider to connect its headquarters to its branch offices only during office hours (e.g., from 7:00 AM to 8:00 PM) or to connections requested to make a large database backup during the night (e.g., from 1:00 AM to 3:00 AM). In these cases, the customer company can indicate the connections’ set-up and tear-down dates because it knows in advance its office hours and and its database backup schedule\(^3\). Scheduled connections were originally investigated under the name of Scheduled Lightpath Demands (SLDs) in the context of WDM optical transport network optimization [7–10].

Though permanent and scheduled connections can potentially support most of the (fairly predictable) enterprise traffic offered to transport networks, switched (i.e., random) connections are still needed to cope with unexpected shifts in the traffic demand. These shifts may result from outages not considered in the protection plan of the network or, in networks transporting a large volume of public Internet traffic, from phenomena like flash crowds and worms [5, 6]. The joint provisioning of scheduled and switched connections in optical transport networks has been recently investigated [7, 8]. In this article we focus on the provisioning of scheduled connections in SDH networks and leave the joint provisioning of scheduled and switched connections for further study.

Protection of the SCDs is considered in this study using a Shared Backup Path Protection (SBPP) approach [9]. In SBPP, the primary path (also known as working path) of an SCD is protected end-to-end by a span- or node-disjoint backup path (also known as protection path) using shared spare capacity. Sharing is arranged among the backup paths associated with other primary paths that are failure-disjoint from the current primary path.

The contribution of this study is two-fold: we mathematically model and solve the problem of instantiating protected SCDs in both CCAT- and VCAT-capable SDH networks, and we assess the gain in terms of network resources provided by the latter with respect to the former.

The next section presents a detailed description of the problem under consideration. Section III describes the mathematical model used to represent the RSAc and RSAv problems (Routing and Slot Assignment in CCAT- and VCAT-capable networks, respectively) as combinatorial optimization problems. Section IV presents the problem-specific elements of the Simulated Annealing (SA) based meta-heuristic algorithm used to compute approximate solutions to instances of the RSAc and RSAv problems. In Section V we experimentally evaluate the gain in network resources provided by VCAT. Finally, Section VI presents our conclusions and discusses directions of future work.

### II. DESCRIPTION OF THE PROBLEM

We consider an SDH transport network formed by nodes interconnected by spans in an arbitrary (mesh) topology. Each node hosts an SDH Digital Cross-Connect (D XC) able to originate, terminate and switch VC-4 connections. A span is a collection of optical fibers connecting two adjacent nodes. All the fibers in a span are contained into a single cable or duct and share the same fate in the event of a cut of the cable. The optical fibers are directional in the sense that the information “flows” in one direction. The set of the fibers in the span transferring information in one direction is called a link. The span has two direction-opposed links. A link implements one or more STM-N frames. An STM-N frame has \( N \) time slots. Each of these time slots can be used to bear a VC-4 connection on the slot’s link.

Figure 1 shows the typical architecture of a DXC: a chassis hosts a switching matrix\(^4\) connected via a back plane to interface cards. Each interface card hosts a fixed number of ports which are used to either terminate a connection (traffic being added or dropped at the DXC) or to transmit a connection over a long distance. The former are referred to as Short Range ports (SR) and the latter as Long Haul (LH) ports. An interface card usually hosts either SR or LH ports, but not both. Cards hosting LH ports are relatively more expensive than cards hosting SR ports because of the sophisticated opto-electronic devices required to transmit signals over long distances (boosters, pre-amplifiers, etc.). This high cost justifies the minimization of the global number of STM-N frames in the network’s links as the optimality criterion in the Routing and Slot Assignment problem explained later (a LH port is required on each DXC at the end of a link to support a STM-N frame over that link).

In this paper we consider DXCs with a non-blocking matrix able to switch individual VC-4 connections. The DXCs can host four types of cards: “8 × VC4-16c” SR, “8 × STM-16” LH, “8 × VC4/4c” SR and “8 × GbE/GFP-X” SR. The “8 × VC4-16c” SR card terminates up to 8 VC4-16c connections. Each port on the front panel has two associated ports on

<table>
<thead>
<tr>
<th>No.</th>
<th>s</th>
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<td>8</td>
<td>1</td>
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<td>14:40</td>
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<tr>
<td>δ₂</td>
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<td>7</td>
<td>3</td>
<td>11:00</td>
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<tr>
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<td>1</td>
<td>6</td>
<td>2</td>
<td>17:00</td>
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The following simplifying assumptions are made:

- The SDH Digital CrossConnects (DXCs) are all of the same type: either CCAT- or VCAT-capable DXCs;
- The same type of STM-N frame is used on all the links of the network: either STM-1, STM-4, STM-16, STM-64 or STM-256;
- The switching capacity in the DXCs and the number of STM-N frames on a link are unlimited;
- The n VC-4 connections of a same SCD are routed through the same primary and backup pair of paths (i.e., bifurcated routing is not allowed neither in CCAT- nor in VCAT-capable networks);
- In the RSA problem in CCAT-capable networks, the size of the SCDs, n, is never greater than the STM-N frame size, and
- The network is protected against a single span failure (complete protection against multiple span failures is not guaranteed).

### III. Mathematical model

The problem of Routing and Slot Assignment for protected SCDs (RSA) is formulated as a combinatorial optimization problem. Two versions of the problem are defined: RSA in VCAT-capable networks (RSAv) and RSA in CCAT-capable networks (RSAc). The following subsection defines the notations common to the two versions. Subsections III-B and III-C define the notations specific to the RSAv and RSAc problems, respectively.

#### A. Common notations

\[ G = (V, E, w) \]

is an arc-weighted symmetrical directed graph with vertex set \( V = \{v_1, v_2, \ldots, v_N\} \), arc set \( E = \{e_1, e_2, \ldots, e_L\} \) and weight function \( w : E \rightarrow \mathbb{R}^+ \). The graph represents a telecommunication network. The set \( V \) corresponds to the network nodes. An arc \( e \in E \) represents a link. Function \( w \) maps a cost on each span (e.g., physical length of the span or any other value defined by the operator).

\[ U = \{(e, e') \mid e, e' \in E, s(e) = d(e'), d(e) = s(e')\} \]

is the set of spans in the network. A span is represented by a pair of arcs \( e, e' \in E \) such that the source of one of the arcs is the destination of the other and vice versa. Hereafter, it is important to keep in mind the difference between an arc and a span.

\[ N = |V|, L = |E|, S = |U| = L/2 \]

are, respectively, the number of vertices, arcs and spans in \( G \). Note that \( L/2 \) is integral because \( G \) is symmetrical.

\( F \)

is the size of the STM frames (in number of slots) used on the arcs of \( G \). Valid sizes in this study are 4, 16, 64 and 256.

As indicated before, all the frames in the network are of the same size.
\( \Delta = \{ \delta_1, \delta_2, \ldots, \delta_M \} \)
is the set of \( M \) SCDs, where
\[
\delta_i = (s_i, d_i, n_i, \alpha_i, \omega_i)
\]
is a tuple representing the SCD number \( i \); \( s_i, d_i \in V \) are the source and destination nodes of the demand, \( n_i \) is the number of requested VCs connections, and \( \alpha_i \) and \( \omega_i \) are the set-up and tear-down dates of the demand, respectively.

\((G, \Delta)\) is a pair representing an instance of the RSA problem. Note that the dates \( \alpha_i \) and \( \omega_i \) are part of the problem instance (i.e., they are part of the input parameters of the problem and not decision variables).

\( P_{k,i} \), \( 1 \leq k \leq K \), \( 1 \leq i \leq M \) represents the \( k^{th} \) alternate primary path in \( G \) from \( s_i \) to \( d_i \). For the purposes of this article, we compute the \( K \) physically\(^5\) shortest paths (if so many exist) for each demand using the algorithm defined in [10]. However, the paths might be defined according to any other criterion (i.e., the function \( w \) may map any other value than the spans’ length). The considered paths are loop-free.

\( P'_{k,i} \), \( 1 \leq k \leq K \), \( 1 \leq i \leq M \) represents the \( k^{th} \) alternate backup path in \( G \) from \( s_i \) to \( d_i \). \( (P_{k,i}, P'_{k,i}) \) represents the \( k^{th} \) couple of arc-disjoint paths between \( s_i \) and \( d_i \). Two paths \( P_{j,a} \) and \( P_{k,b} \) must be arc-disjoint only if \( j = k \) and \( a = b \), i.e., when they are associated as a couple of primary and backup paths for a same SCD. In this study, \( P'_{k,i} \) is the \( k^{th} \) path computed with the algorithm defined in [10] on the graph \( G' = (V, E') \), where \( E' = E \setminus P_{k,i} \) so that \( P_{k,i} \) and \( P'_{k,i} \) are arc-disjoint.

\[ \pi^a_{\rho,\Delta} = \{ P_{\rho,1}, P_{\rho,2}, \ldots, P_{\rho,M,M} \}, \rho \in \{1, \ldots, K\}^M \]
is called an admissible routing solution for \( \Delta \). \( \rho \) is an \( M \)-dimensional vector whose elements can take a value between 1 and \( K \). The vector represents the set of decision variables of the problem. An admissible routing solution is fully characterized by \( \rho \).

\[ \pi^b_{\rho,\Delta} = \{ P'_{\rho,1}, P'_{\rho,2}, \ldots, P'_{\rho,M,M,M} \}, \rho \in \{1, \ldots, K\}^M \]
is the tuple of backup paths \( P'_{\rho,k} \) associated to the primary paths \( P_{\rho,k} \) and is called the backup solution associated to \( \pi^a_{\rho,\Delta} \). An admissible routing solution has only one associated backup solution.

\[ \Pi_{\Delta} = \{ (\pi^a_{\rho,\Delta}, \pi^b_{\rho,\Delta}) \mid \rho \in \{1, \ldots, K\}^M \} \]
is the set of solution pairs \( (\pi^a_{\rho,\Delta}, \pi^b_{\rho,\Delta}) \) for \( \Delta \). There are \(|\Pi_{\Delta}| = K^M \) solution pairs in the set (if there exist at least \( K \) couples \( (P_{k,i}, P'_{k,i}) \) of arc-disjoint paths for each demand; otherwise, \(|\Pi_{\Delta}| < K^M \)). Hereafter we use the generic term solution to refer to either an admissible routing solution \( \pi^a_{\rho,\Delta} \) or a backup solution \( \pi^b_{\rho,\Delta} \). We denote this solution by \( \pi_{\rho,\Delta} \).

\[ \Delta_{e}^{\pi^a_{\rho,\Delta}} = \{ \delta_i \in \Delta \mid e \in P_{\rho,i} \} \]
is the subset of SCDs whose primary path \( P_{\rho,i} \) contains the arc \( e \in E \) when using admissible routing solution \( \pi^a_{\rho,\Delta} \). For the sake of simplicity, we note \( \Delta^a_e \) instead of \( \Delta_{e}^{\pi^a_{\rho,\Delta}} \).

\[ \Delta_{e}^{\pi^b_{\rho,\Delta}} = \{ \delta_i \in \Delta \mid e \in P'_{\rho,i} \} \]
is the subset of SCDs whose backup path \( P'_{\rho,i} \) contains the arc \( e \in E \) when using backup solution \( \pi^b_{\rho,\Delta} \). For the sake of simplicity, we note \( \Delta^b_e \) instead of \( \Delta_{e}^{\pi^b_{\rho,\Delta}} \).

\[ \Delta_e = \Delta^a_e \cup \Delta^b_e \]
is the subset of SCDs, \( \Delta_e \subseteq \Delta \), whose primary or backup path contains the arc \( e \) when using solution pair \( (\pi^a_{\rho,\Delta}, \pi^b_{\rho,\Delta}) \). Because the paths \( (P_{k,i}, P'_{k,i}) \) of an SCD \( \delta_i \) are arc-disjoint (for a same \( k \)), an arc \( e \) may be part of either \( P_{k,i} \) or \( P'_{k,i} \), but not of both. In other words, \( \Delta^a_e \cap \Delta^b_e = \emptyset \).

\[ \theta = (\theta_{ij}) \]
is a \( \{0, 1\}^{M \times M} \) upper triangular matrix; \( \theta_{ij}, i \leq j \), indicates whether the SCDs \( \delta_i \) and \( \delta_j \) overlap in time (\( \theta_{ij} = 1 \)) or not (\( \theta_{ij} = 0 \)). By definition \( \theta_{ii} = 1, 1 \leq i \leq M \), and \( \theta_{ij} = 0 \) for \( i > j \). This matrix expresses the temporal relationship between the SCDs.

\[ \gamma^a_{\rho,\Delta} = \{ \gamma^a_{ij} \} \]
is a \( \{0, 1\}^{S \times M} \) span-path incidence matrix; \( \gamma^a_{ij} \) indicates whether at least one of the arcs of span \( i \in U \) is part of path \( P_{\rho,j} \) (\( \gamma^a_{ij} = 1 \)) or not (\( \gamma^a_{ij} = 0 \)) in admissible routing solution \( \pi^a_{\rho,\Delta} \). For the sake of simplicity, we note \( \gamma \) instead of \( \gamma^a_{\rho,\Delta} \).

\[ \phi = \gamma^T, \gamma = (\phi_{ij}) \]
is an \( M \times M \) matrix; \( \phi_{ij} \) is the number of spans on admissible routing solution \( \pi^a_{\rho,\Delta} \) for which SCD \( \delta_i \) overlaps with SCD \( \delta_j \).

\[ E^a = \{ (\delta_i, \delta_j) \in \Delta^a_e \times \Delta^a_e \mid \theta_{ij} = 1 \} \]
is a set of time-overlapping SCD couples whose primary paths contain the arc \( e \) (in admissible routing solution \( \pi^a_{\rho,\Delta} \)).

\[ E^b = \{ (\delta_i, \delta_j) \in \Delta^b_e \times \Delta^b_e \mid \theta_{ij} = 1, \phi_{ij} > 0 \} \]
is a set of time-overlapping SCD couples whose backup paths contain arc \( e \) (in backup solution \( \pi^b_{\rho,\Delta} \)) and whose primary paths (in admissible routing solution \( \pi^a_{\rho,\Delta} \)) have at least one common span \( \phi_{ij} > 0 \).

\[ E^{ab} = \{ (\delta_i, \delta_j) \in \Delta^a_e \times \Delta^b_e \mid \theta_{ij} = 1 \} \]
is a set of time-overlapping SCD couples, such that one of them belongs to \( \Delta^a_e \) and the other to \( \Delta^b_e \).

\[ G_e = (\Delta_e, E_e) \]
is an (undirected) conflict graph associated to arc \( e \in E \) for

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\(^5\)The function \( w \) maps the length of each span.
solution pair \((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})\). Each vertex of \(G_e\) represents an SCD of \(\Delta_e\). The edge set is defined as \(E_e = E^a_e \cup E^b_e \cup E^{rb}_e\). The graph formalizes the slot assignment problem on a particular arc \(e\) for a solution pair \((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})\).

In the edge set definition given above, note that the time overlap (\(\theta_{ij} = 1\)) between two SCDs, \(\delta_i\) and \(\delta_j\), is a sufficient condition for an edge to exist between these SCDs in \(G_e\), provided that at least one of the SCDs uses the arc \(e\) as part of its primary path.

**B. RSA with virtual concatenation**

\[ B^v : \Pi_\Delta \rightarrow \mathbb{N} \]

is the cost function that computes an upper bound on the number of STM-N frames required by a solution pair \((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})\) when the network is VCAT-capable. The following notations are necessary to describe this function:

\( A \) is a deterministic algorithm that finds a proper coloring for a given graph \(G\). A proper coloring of a graph \(G = (V, E)\) is a mapping of vertices to colors \(c : V \rightarrow \mathbb{N}\) such that \(c(u) \neq c(v)\) if \((u, v) \in E\), i.e., any two vertices connected by an edge are assigned different colors [11]. For the purposes of this study, we use a polynomial-time sequential algorithm called Largest-First First-Fit (LFFF) to compute a proper coloring [12]. The algorithm defines a proper coloring with a number of colors \(\chi'(G)\) hopefully close to the chromatic number\(^6\) \(\chi(G)\) of \(G\), i.e., \(\chi'(G) \geq \chi(G)\). Finding a proper coloring with exactly \(\chi(G)\) colors is an NP-complete problem [13].

\[ \Delta_{e,i}, \ 1 \leq i \leq \chi'(G_e) \]

is the subset \(\Delta_{e,i} \subseteq \Delta_e\) of SCDs whose vertices in \(G_e\) have been colored with color \(i\) using \(A\). \(\chi'(G_e)\) is the number of colors used by \(A\) to color \(G_e\).

The cost function \(B^v\) is defined as:

\[
B^v((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})) = \sum_{e \in E} \kappa(G_e). \tag{1}
\]

where

\[
\kappa(G_e) = \left[ \frac{\sum_{i=1}^{\chi'(G_e)} \max\{n_j | \delta_j \in \Delta_{e,i}\}}{F} \right] \tag{2}
\]

is the cost of \(G_e\) when colored with \(A^r\). In fact, \(\kappa(G_e)\) corresponds to the number of STM-N frames required on arc \(e\) for a given solution pair \((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})\) when the network is VCAT-capable.

Thus, the RSAv problem is formally defined by the following combinatorial optimization problem:

\( ^6\)The minimum number of colors required for a proper coloring of \(G\).

\( ^7\lceil x \rceil \) is the smallest integer greater than or equal to \(x\).

\[
\text{Minimize: } B^v((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})), \tag{3}
\]

subject to:

\[
(\pi^a_{p,\Delta}, \pi^b_{p,\Delta}) \in \Pi_\Delta. \tag{4}
\]

Ideally, we would like to minimize \(\kappa(G_e)\), whereas the LFFF algorithm aims at minimizing \(\chi'(G_e)\). These two objectives are not equivalent and this will explain some discrepancies in the results presented further. We selected the LFFF algorithm for practical reasons. The Simulated Annealing (SA) algorithm (described later) evaluates tens of thousands of different solution pairs \((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})\). When solving the RSAc problem, a conflict graph \(G_e\) must be built and colored for each arc \(e\). Consequently, \(A\) must have a low time-complexity (which is the case of LFFF) in order for the SA algorithm to be usable on problem instances of large size. We could get a value of \(\kappa(G_e)\) closer to the minimal one by implementing a low time-complexity Local Descent (LD) algorithm that takes as input a solution computed by LFFF and iteratively decreases \(\kappa(G_e)\) by moving from a proper coloring solution to a neighbor one until no further improvements are possible.

**C. RSA with contiguous concatenation**

\( \varphi : \Delta \rightarrow \{1, 4, 16, 64, 256\} \)

is a function that indicates the number of slots required in continuous concatenation to bear a particular SCD. The function is defined as:

\[
\varphi(\delta_i) = \begin{cases} 1, & n_i = 1 \\ 4, & 1 < n_i \leq 4 \\ 16, & 4 < n_i \leq 16 \\ 64, & 16 < n_i \leq 64 \\ 256, & 64 < n_i \leq 256. \end{cases} \tag{5}
\]

\( B^c : \Pi_\Delta \rightarrow \mathbb{N} \)

is the cost function that computes an upper bound on the number of STM-N frames required by a solution pair \((\pi^a_{p,\Delta}, \pi^b_{p,\Delta})\) when the network is CCAT-capable. The following notations are necessary to describe this function:

\( B \) is a deterministic algorithm that computes a set-coloring for \(G_e\). A set-coloring \(s\) of a graph \(G = (V, E)\) is a mapping of vertices \(v \in V\) to sets of colors \(s(v) \subset \mathbb{N}\) such that \(\forall (u, v) \in E, s(u) \cap s(v) = \emptyset\) [14]. In the problem under consideration in this subsection, we define additional constraints on the sets \(s(\delta_i), \delta_i \in \Delta_e\), to represent the constraints imposed by the contiguous concatenation mechanism on slot assignment. Namely, for all \(\delta_i \in \Delta_e\):

- \(|s(\delta_i)| = \varphi(\delta_i)\),
- the elements of \(s(\delta_i)\) are consecutive integers and
- the largest element in \(s(\delta_i)\) is a multiple of \(\varphi(\delta_i)\), i.e., \(\max s(\delta_i) \equiv 0 (mod \varphi(\delta_i))\).
For the purposes of this study, we propose a modified version of the LFFF algorithm that takes into account these constraints when coloring $G_e$. The algorithm defines a set-coloring with a number of colors $\chi_s(G)$ hopefully close to the set-chromatic number\(^8\), $\chi_s(G) \geq \chi_s(G)$.

The cost function $B^c$ is defined as:

$$B^c((\pi^{a}_{\rho, \Delta}, \pi^{b}_{\rho, \Delta})) = \sum_{e \in E} \left[ \frac{\chi_s(G_e)}{F} \right]. \quad (6)$$

Thus, the RSAc problem is formally defined by the following combinatorial optimization problem:

**Minimize:** $B^c((\pi^{a}_{\rho, \Delta}, \pi^{b}_{\rho, \Delta})),$ \quad (7)

**subject to:**

$(\pi^{a}_{\rho, \Delta}, \pi^{b}_{\rho, \Delta}) \in \Pi_{\Delta}.$ \quad (8)

D. A numerical example

The notations described in the preceding sections are illustrated by the example presented in Figure 2. We represent a network and a particular routing solution for the three SCDs of Table I consisting of a pair of working and backup paths for each SCD. The right side of the figure shows the conflict graph $G_{(9,10)}$. The graph has vertex set $\Delta_{(9,10)} = \Delta^a_{(9,10)} \cup \Delta^b_{(9,10)} = \{\delta_1, \delta_2, \delta_3\}$ and arc set $E_{(9,10)} = E^a_{(9,10)} \cup E^b_{(9,10)} = \{(\delta_1, \delta_2), (\delta_1, \delta_3)\}$. A possible proper coloring for this graph is given by $c(\delta_1) = 1, c(\delta_2) = 2, c(\delta_3) = 3$. This proper coloring requires $\chi_s(G_{(9,10)}) = 3$ colors and yields sets $\Delta_{(9,10),1} = \{\delta_1, \delta_2\}$ and $\Delta_{(9,10),2} = \{\delta_3\}$. Assuming an STM frame of size $F = 4$, we get:

$$\kappa(G_e) = \left\lceil \frac{\max(1,2) + \max(3)}{4} \right\rceil = 2. \quad (9)$$

A possible set-coloring (see § III-C) for the same graph is given by $s(\delta_1) = \{1\}, s(\delta_2) = \{5, 6, 7, 8\}$ and $s(\delta_3) = \{1, 2, 3, 4\}$. This set-coloring requires $\chi_s(G_{(9,10)}) = 8$ colors, which means that $|8/4| = 2$ STM-4 frames are required on link $(9,10)$ for the particular routing solution in a CCAT-capable network.

IV. SIMULATED ANNEALING BASED ALGORITHM

In this study we propose to use a Simulated Annealing (SA) based iterative meta-heuristic algorithm [15] to find approximate solutions to instances of the the RSAv and RSAc problems. In terms of algorithms, the contribution of this paper is the application of SA to the problem under consideration, rather than the SA algorithm itself, which is well-known. Meta-heuristics are widely used in practice because, in general, they are able to deal with problem instances of realistic size and, at the same time, provide satisfactory solutions. We call

SAv and SAc the versions of the SA algorithm that solve the RSAv and RSAc problems, respectively.

Simulated Annealing is a generic algorithm that can be applied to a variety of optimization problems as long as one can supply three problem-specific elements: a) an initial solution, b) a cost function to evaluate the solutions generated by the algorithm and c) a perturbation procedure to generate a new solution from a current one. We define these three elements for SAv and SAc in the following paragraphs. The generic SA algorithm is described in [15] and is not reproduced here because of limited space.

Remember from Subsection III-A that a solution pair $(\pi^{a}_{\rho, \Delta}, \pi^{b}_{\rho, \Delta})$ is fully characterized by a vector $\rho$. Hereafter, we use vector $\rho$ to refer to the $(\pi^{a}_{\rho, \Delta}, \pi^{b}_{\rho, \Delta})$ solution pair.

We select as initial solution the vector $\rho$ whose components are all equal to 1. The cost functions for SAv and SAc are defined by (1) and (6), respectively. Finally, the perturbation procedure is defined by the following steps:

1) Generate a pseudo-random number $i$, uniformly distributed in the interval $[1, M]$.
2) Generate a pseudo-random number $j$, uniformly distributed among the elements of the set $\{1, \ldots, K\} \setminus \{\rho_i\}$.
3) Generate a new vector $\rho'$ by replacing $\rho_j$ by $j$ in $\rho$.

For example, vector $\rho = (2, 1, 3)$ can be "perturbed" according to this procedure and lead to vector $\rho' = (2, 3, 1, 3)$.

An SA algorithm iteratively explores the solution space until a stop condition is satisfied. In the implementation considered in this study, the algorithm stops when a fixed number of iterations have been executed.

V. EXPERIMENTAL EVALUATION

The purpose of the experimental evaluation is to assess the gain in terms of STM-N frames provided by VCAT with respect to CCAT under the same traffic and network topology conditions.

We first describe the parameters common to all the experiments. Figure 3 shows the graph $G$ used for all the
problem instances \((G, \Delta)\) investigated in this section. The graph represents the topology of the GÉANT pan-European network\(^9\) \cite{16}. The network has 17 nodes and 26 spans. We assume that STM-16 frames are used on all the links. The SAv and SAc algorithms were implemented in C++ and executed on a SunFire 280R computer.

We compute the average gain for two hypothetical situations. We first consider the case of a “conventional” network operator that offers WAN connectivity services for widely adopted data networking technologies, and SDH connections for the PSTN trunk network (voice traffic). Table II(a) shows the nominal rate of connections based on these technologies. The configuration and percentage of utilization of the CCAT and VCAT SDH connections used to transport these signals are also indicated. We also consider the case of a new entrant operator that offers exclusively innovative services such as MPLS VPNs with LSPs of adequate size or fractional Ethernet private lines. The operator maps these services’ signals onto SDH connections using GFP. Table II(b) shows configuration and percentage of utilization of the CCAT and VCAT SDH connections used to transport the resulting GFP-mapped signals.

In Table III we define traffic scenarii based on the conventional and innovative profiles of Table II. A scenario specifies for each signal type the percentage of traffic load, in a \(\Delta\) set of \(M = 700\) SCDs, associated to this type. For example, Scenario 1.1 specifies that 24% of the traffic load in a \(\Delta\) set of \(M = 700\) SCDs corresponds to Fast Ethernet lines, 4% to ESCON lines and so on. Scenario 2.1 represents the case in which all the GFP-mapped signals are equally represented in the traffic load whereas Scenario 2.2 represents a hypothetical case in which the fraction of a signal type in the traffic load is inversely proportional to its rate (this may be the case of an operator selling “retail” services). For each scenario, we generated five \(\Delta\) sets with strong time correlation\(^10\), \(\tau(\Delta) \approx 0.9\), and five \(\Delta\) sets with weak time correlation, \(\tau(\Delta) \approx 0.1\). For each \(\Delta\) set, the source/destination nodes and the set-up/tear-down dates of the SCDs were drawn from uniform distributions in the intervals \([1, 1440]\) and \([1, 11440]\), respectively\(^11\). The set-up/tear-down dates were constrained to satisfy the target time correlation value of the set (either \(\tau(\Delta) \approx 0.9\) or \(\tau(\Delta) \approx 0.1\)).

The SAv and SAc algorithms were used to minimize the number of STM-16 frames required to instantiate the SCDs of a \(\Delta\) set. Figure 4 shows the average number of STM-16 frames (over the five \(\Delta\) sets) for each scenario when CCAT or VCAT is used to instantiate SCDs in \(\Delta\) sets with strong and weak time correlation (Figures 4(a) and 4(b), respectively).

The number of required STM-16 frames is greater for \(\Delta\) sets with strong time correlation than for \(\Delta\) sets with weak time correlation because, in general, the maximum number of time-overlapping connections passing through a network link decreases as the time correlation does; the link is dimensioned for this number of connections. In Figure 4(a), the gain of VCAT in terms of frames with respect to CCAT is 9.67%, 15.30% and 19.54% for scenarii 1.1, 1.2 and 1.3, respectively. The gain increases as the fraction of data traffic does (from 40% to 80%) because the possibility of exploiting the flexibility of VCAT to efficiently accommodate diverse connection sizes increases. For the innovative services profile the gain for scenarii 2.1 and 2.2 is 33.39% and 37.30%, respectively. In Figure 4(b), the gain is -7.70%, -7.76% and 2.08% for scenarii 1.1, 1.2 and 1.3, respectively, and -2.98% and 6.57% for scenarii 2.1 and 2.2. The gain is negative in some cases (i.e., more frames are required with VCAT than with CCAT) because of the mismatch between the optimality criterion defined for algorithm A and the optimality goal of the LFFF algorithm implemented in this paper, \(\chi(G_\tau)\) (see § III-B). Such a mismatch does not exist in the RSAc problem. The gain is always positive in the strong time correlation scenarii. Though the fraction of data traffic for, say Scenario 1.1, is the same with strong and with weak time correlation, the total volume of traffic (and hence of data traffic) is higher in the former than in the latter case. Thus, in strong time correlation scenarii, the gain provided by the resource efficiency of VCAT on this (higher) volume of data traffic is large enough to hide the negative effect of the optimality criterion mismatch.

Table IV shows for each scenario the average number of interface cards required to implement the solution computed by the SAc and SAv algorithms under strong time correlation. “8 × VC4/4c” and “8 × VC4-16c” cards are used to terminate CCAT connections and “8 × GbE/GFP-X” cards are used to terminate VCAT connections. “8 × STM-16” cards are used in both types of networks to implement the STM-16 frames on the links. The “% LH” column indicates for each scenario the average number of required LH cards expressed as a fraction

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\(^9\)Only nodes terminating 2.5 or 10 Gbps links (as described in the network at its stage in November 2003) are represented. For the complete, up-to-date topology, see \cite{16}.

\(^10\)For a description of the time correlation formula \(\tau(\Delta)\), see § III-B of [3]. The formula is not described here because of limited space.

\(^11\)1440 is the number of minutes in a 24-hour period.
of the average total number of required cards. The average total number of cards for each scenario is in general lower with VCAT than with CCAT. Moreover, the fraction of LH cards is lower with VCAT than with CCAT. If LH cards represent the dominant cost of a network, the introduction of VCAT results in a smaller number of such cards and hence in a lower network cost.

VI. CONCLUSIONS AND FUTURE WORK

In this article we developed mathematical formulations of the protected SCD Routing and Slot Assignment problem (RSA) in CCAT- and VCAT-capable networks. Instances of the problem are solved using a Simulated Annealing algorithm for which the problem-specific elements were presented. We used the algorithm to assess the gain in terms of STM-16 frames (LH interfaces) provided by VCAT with respect to CCAT. We found that this gain increases as the fraction of connections not fitting CCAT standard connection sizes increases. Our numerical results outline the benefits of VCAT, particularly in the context of innovative services such as the transport of fractional Ethernet signals.

We currently investigate the adaptation and integration of the models and algorithms proposed in this paper into a generic IP over SDH network provisioning or planning system. The system can be used, for example, to determine whether restoration at the IP level, SBPP at the SDH level or a combination of them better satisfy the performance and cost requirements of a particular network operator. It may also be used as the basis of an operational network engineering tool.

REFERENCES

TABLE IV
AVERAGE NUMBER OF CARDS AND PERCENTAGE OF LONG Haul CARDS FOR DIFFERENT TRAFFIC SCENARIO UNDER STRONG TIME CORRELATION

<table>
<thead>
<tr>
<th>Scenario</th>
<th>(A)-cards</th>
<th>(B)-cards</th>
<th>(D)-cards</th>
<th>Total</th>
<th>% LH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>177.2</td>
<td>16.2</td>
<td>73.8</td>
<td>267.2</td>
<td>27.61</td>
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<td>1.2</td>
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<td>52.63</td>
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<td>161.4</td>
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<td>45.69</td>
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</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>(C)-cards</th>
<th>(D)-cards</th>
<th>Total</th>
<th>% LH</th>
</tr>
</thead>
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<td>68.2</td>
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