Intra-Domain Pathlet Routing

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Abstract—Internal routing inside an ISP network is the foundation for lots of services that generate revenue from the ISP's customers. A fine-grained control of paths taken by network traffic once it enters the ISP's network is therefore a crucial means to achieve a top-quality offer and, equally important, to enforce SLAs. Many widespread network technologies and approaches (most notably, MPLS) offer limited (e.g., with RSVP-TE), tricky (e.g., with OSPF metrics), or no control on internal routing paths. On the other hand, recent advances in the research community [1] are a good starting point to address this shortcoming, but miss elements that would enable their applicability in an ISP's network.

We extend pathlet routing [1] by introducing a new control plane for internal routing that has the following qualities: it is designed to operate in the internal network of an ISP; it enables fine-grained management of network paths with suitable configuration primitives; it is scalable because routing changes are only propagated to the network portion that is affected by the changes; it supports independent configuration of specific network portions without the need to know the configuration of the whole network; it is robust thanks to the adoption of multipath routing; it supports the enforcement of QoS levels; it is independent of the specific data plane used in the ISP’s network; it can be incrementally deployed and it can nicely coexist with other control planes. Besides formally introducing the algorithms and messages of our control plane, we propose an experimental validation in the simulation framework OMNeT++ that we use to assess the effectiveness and scalability of our approach.

I. INTRODUCTION

It is unquestionable that routing choices inside the network of an Internet Service Provider (ISP) are critical for the quality of its service offer and, in turn, for its revenue, and several technologies have been introduced over time to provide ISPs with different levels of control on their internal routing paths. These technologies, ranging from approaches as simple as assigning costs to network links (like, e.g., in OSPF) to real traffic engineering solutions (like, e.g., RSVP), usually fall short in at least one among: complexity of setup, predictability of the effects, and degree of control on the routing paths. The research community has worked and still contributes to this hot matter from different points of view: control over paths is attained by means of source routing techniques; besides this, many papers advocate the use of multipath routing as a means to ensure resiliency and quick recovery from failures; moreover, the granularity of the routing information to be disseminated to support multipath and source routing is sometimes controlled by using hierarchical routing mechanisms. However, to the extent of our knowledge, existing technological and research solutions still fail in conjugating a fine-grained control of network paths, support for multipath, differentiation of Quality of Service levels, and the possibility to independently configure different network portions, a few goals that an ISP is much interested in achieving without impacting the simplicity of configuration primitives, the scalability of the control plane (in terms of consumed device memory and of exchanged messages, especially in the presence of topological changes), the robustness to faults, and the compatibility with existing deployed routing mechanisms.

In this paper we propose the design of a new control plane for internal routing in an ISP’s network which combines all these advantages. Our control plane is built on top of pathlet routing [1], which we believe to be one of the most convenient approaches introduced so far to tackle the ISP’s requirements described above.

The foundational principles of our control plane are as follows. A pathlet is a path fragment described by a t-uple \((FID, v_1, v_2, \sigma, \delta)\), the semantic being the following: a pathlet, identified by a value \(FID\), describes the possibility to reach a network node \(v_2\) starting from another network node \(v_1\), without specifying any of the intermediate devices that are traversed for this purpose. A pathlet need not be an end-to-end path, but can represent the availability of a route from an intermediate system \(v_1\) to an intermediate system \(v_2\) in the ISP’s network. An end-to-end path can then be constructed by concatenating several pathlets. The \(\delta\) attribute carries information about the network destinations (e.g., IP prefixes) that can be reached by using that pathlet. Besides pathlets are not necessarily end-to-end, this attribute can be empty. In the control plane we propose, routers are grouped into areas: an area is a portion of the ISP’s network wherein routers exchange all information about the available links, in a much similar way to what a link-state routing protocol does; however, when announced outside the area, such information is summarized in a single pathlet that goes from an entry router for the area directly to an exit router, without revealing routing choices performed by routers that are internal to the area. This special pathlet, which we call crossing pathlet, is considered outside the area as if it were a single link. An area can enclose other areas, thus forming a hierarchical structure with an arbitrary number of levels: the \(\sigma\) attribute in a pathlet encodes a restriction about the areas where that pathlet is
supposed to be visible.

In designing our control plane we took into account several aspects, among which: efficient reaction to topological changes and administrative configuration changes, meaning that the effects of such changes are only propagated to the network portion that is affected by them; support for several kinds of routing policies; support for multipath and differentiation of QoS levels; and compatibility and integration with other technologies that are already deployed in the ISP’s network, to allow an incremental deployment. By introducing areas we also offer the possibility for different network administrators to independently configure different portions of an ISP’s network without the need to be aware of the overwhelmingly complex setup of the whole network.

Our contribution consists of several parts. First of all, we introduce a model for a network where nodes are grouped in a hierarchy of areas. Based on this model, we define the basic mechanisms adopted in the creation and dissemination of pathlets in the network. We then present a detailed description of how network dynamics are handled, including the specification of the messages of our control plane and of the algorithms executed by a network node upon receiving such messages or detecting topological or configuration changes. Further, we elaborate on the practical applicability of our control plane in an ISP’s network in terms of possible deployment technologies and propose some possible extensions to accommodate further requirements. Last, we present an experimental assessment of the scalability of our approach in a simulated scenario.

The rest of the paper is organized as follows. In Section II we review and classify the state of the art on routing mechanisms that could match the requirements of ISPs. In Section III we introduce our formal network model. In Section IV we describe the basic pathlet creation and dissemination mechanisms. In Section V we detail the message types of our control plane and describe the network dynamics. In Section VI we present applicability considerations and possible extensions to accommodate other requirements. In Section VII we present the results of our experiments run in the OMNeT++ simulation framework. Last, conclusions and plan for future work are presented in Section VIII.

II. RELATED WORK

Many of the techniques that we adopt in our control plane have already been proposed in the literature. Most notably, these techniques include source routing (intended as the possibility for the sender of a packet to select the nodes that the packet should traverse), hierarchical routing (intended as a method to hide the details of routing paths within certain portions of the network by defining areas), and multipath routing (intended as the possibility to compute and keep multiple paths between each source-destination pair). However, none of the contributions we are aware of combines them in a way that provides all the benefits offered by our approach. We provide Table I as a reading key to compare the state of the art on relevant control plane mechanisms, discussed in the following.

Pathlet routing [1] is probably the contribution that is closest to our control plane approach: its most evident drawback is the lack of a clearly defined mechanism for the dissemination of pathlets, which the authors only hint at. Path splicing [2] is a mechanism designed with fault tolerance in mind (see also [13]): it exploits multipath to ensure connectivity between network nodes as long as the network is not partitioned. However, actual routing paths are not exposed, and this limits the control that the ISP could enforce on internal routing. Even in MIRO [11], where multiple paths can be negotiated to satisfy the diverse requirements of end users, there can be no full control of a whole routing path. NIRA [3] compensates this shortcoming, but it is designed only for an interdomain routing architecture, like MIRO, and it relies on a constrained address space allocation, a hardly feasible choice for an ISP that is taken also by Landmark [10]. Slick packets [7] is also designed for fault tolerant source routing, achieved by encoding in the forwarded packets a directed acyclic graph of different alternative paths to reach the destination. Besides the intrinsic difficulty of this encoding, it inherits the limits of the dissemination mechanisms it relies on: NIRA or pathlet routing. BGP Add-Paths [8] and YAMR [12] also address resiliency by announcing multiple paths selected according to different criteria, but they only adopt multipath routing, provide very limited or no support for hierarchical routing, and have some dependencies on the BGP technology. A completely different approach is taken by HLP [4], which proposes a hybrid routing mechanism based on a combination of link-state and path-vector protocols. This paper also presents an in-depth discussion of routing policies that can be implemented in such a scenario. Although this contribution matches more closely our approach, it is not conceived for internal routing in an ISP’s network, it constrains the way in which areas are defined on the network, and it has limits on the configurable routing policies. A similar hybrid routing mechanism called ALVA [9] offers more flexibility in the configuration of areas but, like Macro-routing [5], it does not explicitly envision source routing and multipath routing. HDP [6] is a variant of this approach that, although natively supporting Quality of Service and traffic engineering objectives, is closely bound to MPLS and accommodates source routing and multipath

| Source routing | Hierarchical routing | Multipath routing |
|----------------|----------------------|------------------|
| [2]            | Limited              | Yes              |
| [3]            | Yes                  | No               |
| [4]            | Limited              | No               |
| [5]            | No                   | Yes              |
| [6]            | Limited              | Yes              |
| [7]            | Yes                  | Limited          |
| [8]            | No                   | No               |
| [9]            | No                   | Yes              |
| [10]           | No                   | Yes              |
| [11]           | Limited              | No               |
| [12]           | No                   | Limited          |

TABLE I
A CLASSIFICATION OF THE STATE OF THE ART ACCORDING TO THE ADOPTION OF SOME RELEVANT ROUTING TECHNIQUES.
routing only in the limited extent allowed by this technology.

Some of the papers we mention here also point out an aspect that is key to attain the nice control plane features we are looking for: path-vector protocols allow the setup of complex information hiding and manipulation policies, whereas link-state protocols offer fast convergence with a low overhead. Therefore, a suitable combination of the two mechanisms, which is considered in our approach, should be pursued to inherit the advantages of both.

III. A Hierarchical Network Model

We now describe the hierarchical model we use to represent the network. We model the physical network topology as a graph, with vertices being routers and edges representing links between routers: let $G = (V, E)$ be an undirected graph, where $V$ is a set of vertices and $E = \{(u, v) | u, v \in V \}$ is a set of edges that connect vertices. Fig. 1 shows an example of such graph. We assume that any vertex in the graph is interested in establishing a path to special vertices that represent routers that announce network destinations. Therefore, we introduce a set of destination vertices $D \subseteq V$. We highlight that the same representation can be adopted to capture the topology of overlay networks, while keeping the model unchanged.

In order to improve scalability and limit the propagation of routing information that is only relevant in certain portions of the network, we group vertices into structures called areas. To describe the assignment of a vertex $v \in V$ to an area we associate to $v$ a stack of labels $S(v) = (l_0, l_1, \ldots, l_n)$, where each label is taken from a set $L$. To simplify notation and further reasoning, we assume that $l_0$ is the same for every $S(v)$ and that $\bot \in L$. $\bot$ is a special label that we will use to identify routing information (actually, pathlets) that represents network links. Referring to the example in Fig. 1, we have $L = \{0, 1, 2, 3, \bot\}$, $S(v_1) = S(v_2) = S(v_3) = (0, 1, 3)$, $S(v_4) = S(v_5) = (0, 1)$, $S(v_6) = (0)$, and $S(v_7) = (2, 1)$.

We now define some operations on label stacks that allow us to introduce the notion of area and will be useful in the rest of the paper. Given two stacks $\sigma_1 = (l_1, l_2, \ldots, l_i)$ and $\sigma_2 = (l_{i+1}, l_{i+2}, \ldots, l_n)$, we define their concatenation as $\sigma_1 \circ \sigma_2 = (l_1, l_2, \ldots, l_i, l_{i+1}, l_{i+2}, \ldots, l_n)$. Assuming that $()$ indicates the empty stack, we have that $\sigma \circ () = () \circ \sigma = \sigma$. Given two stacks $\sigma_1$ and $\sigma_2$, we say that $\sigma_2$ strictly extends $\sigma_1$, denoted by $\sigma_1 \subsetneq \sigma_2$, if $\sigma_2$ is longer than $\sigma_1$ and $\sigma_2$ starts with the same sequence of labels as in $\sigma_1$, namely there exists a nonempty stack $\bar{\sigma}$ such that $\sigma_2 = \sigma_1 \circ \bar{\sigma}$. We say that $\sigma_2$ extends $\sigma_1$, indicated by $\sigma_1 \subseteq \sigma_2$, if $\sigma$ can be empty.

We call area $A_\sigma$ a non-empty set of vertices whose stack extends $\sigma$, namely a set $A_\sigma \subseteq V$ such that $\forall v \in A_\sigma : \sigma \subseteq S(v)$. The following property is a consequence of this definition:

Property 3.1: Given a vertex $v \in V$ with stack $S(v)$, $v$ belongs to the following set of areas: $\{A_\sigma \mid \sigma \subseteq S(v)\}$. Our definition of area has a few interesting consequences. First, by Property 3.1, specifying the stack $S(v)$ for a vertex $v$ defines all areas $A_\sigma$, such that $\sigma \subseteq S(v)$. Thus, areas can be conveniently defined by simply specifying the label stacks for all vertices. Considering again the example in Fig. 1, the assignment of label stacks to vertices implicitly defines areas $A(0), A(0 1), A(0 1 3), A(0 2)$, and $A(0 2 1)$ (note that $A(0 2) = A(0 2 1)$). Moreover, areas can contain other areas, thus forming a hierarchical structure. However, areas can never overlap partially, that is, given any two areas $A_1$ and $A_2$, it is always $A_1 \subseteq A_2$ or $A_2 \subseteq A_1$. Also, the first label $l_0$ in any stack plays a special role, because it is: $A(l_0) = V$.

Areas are introduced to hide the detailed internal topology of portions of the network and, therefore, to limit the scope of propagation of routing information. As a general rule, assuming that the internal topology of an area $A_\sigma$ consists of all the vertices in $A_\sigma$ and the edges of $G$ connecting those vertices, our control plane propagates only a summary of this information to vertices outside $A_\sigma$. With this approach in mind, we introduce two additional operators on label stacks, that are used to determine the correct level of granularity to be used in propagating routing information. Given two areas $A_{\sigma_a}$ and $A_{\sigma_b}$, the first operator, indicated by $\Rightarrow$, is used to determine the most nested area that contains both $A_{\sigma_a}$ and $A_{\sigma_b}$, namely the area within which routing information that is relevant only for vertices in $A_{\sigma_a}$ and $A_{\sigma_b}$ is supposed to be confined: this area is defined by $A_{\sigma_a \Rightarrow \sigma_b}$. Referring to the example in Fig. 1, the most nested area containing both $v_5$ and $v_7$ is $A_{S(v_5) \Rightarrow S(v_7)} = A(0)$. The second operator, indicated by $\leftarrow$, is used to determine the least nested area that includes all vertices in $A_{\sigma_a}$ but not those in $A_{\sigma_b}$, namely the area that vertices in $A_{\sigma_a}$ declare to be member of when sending routing information to neighboring vertices in $A_{\sigma_b}$: this area is defined by $A_{\sigma_a \leftarrow \sigma_b}$ (in case $\sigma_a \not\subseteq \sigma_b$, such an area does not exist and $A_{\sigma_a \leftarrow \sigma_b} = A_{\sigma_a}$). Considering again Fig. 1, $v_7$ communicates with $v_5$ as a member of area $A_{S(v_7) \leftarrow S(v_5)} = A(0 2)$. We now define the two operators formally. Given two arbitrary stacks $\sigma_a = (a_0 \ldots a_i \ldots a_n)$ and $\sigma_b = (b_0 \ldots b_i \ldots b_m)$ such that $a_0 = b_0, a_1 = b_1, \ldots, a_i = b_i$ for some $i \leq \min(m, n)$ and $a_{i+1} \neq b_{i+1}$ if $i < \min(m, n)$, we define $\sigma_a \leftarrow \sigma_b = (a_0 \ldots a_i)$ and $\sigma_a \Rightarrow \sigma_b = (a_0 \ldots a_k)$ where $k = \min(i+1, n)$. We extend these definitions in a natural way by assuming that $() \Rightarrow \sigma_b = \sigma_a \Rightarrow () = ()$ and $\sigma_a \leftarrow () = () \Rightarrow \sigma_b = ()$. Be aware that $\Rightarrow$ is commutative, whereas $\leftarrow$ is not.

For each area, a subset of the vertices belonging to the area are in charge of summarizing internal routing information and propagating it outside the area: these vertices are called border vertices. In particular, a vertex $u \in A_\sigma$ incident on
an edge \((u, v)\) such that \(v \notin A_u\) is called a border vertex for area \(A_u\). In the example in Fig.1, \(v_2\) is a border vertex for area \(A_{(0\ 1\ 3)}\) because \(v_2 \in A_{(0\ 1\ 3)}\), \((v_2, v_6) \in E\), and \(v_6 \notin A_{(0\ 1\ 3)}\). Because of Property 3.1, a single vertex can be a border vertex for more than one area: in Fig. 1, \(v_2\) is also a border vertex for area \(A_{(0\ 1)}\) because \(v_2 \in A_{(0\ 1)}\) and \(v_6 \notin A_{(0\ 1)}\). Also, by definition it may be the case that a neighbor of a border vertex is not a border vertex for any areas: looking again at Fig. 1, \(v_6\) is not a border vertex. Derived from the definition of border vertex, we can state the following property:

**Property 3.2:** There can be no border vertex for area \(A_{(lo)}\).

### IV. Basic Mechanisms for the Dissemination of Routing Information

After introducing our network model, we can now illustrate how routing information is disseminated over the network. In order to do so, we first define the concept of pathlet and describe how pathlets are created and propagated. We then introduce conditions on label stacks and routing policies that regulate the propagation of pathlets.

**Pathlets** – In order to learn about paths to the various destinations, vertices in graph \(G\) exchange path fragments called pathlets [1]. In order to support the definition of areas and the consequent information hiding mechanisms, we present an enhanced definition of a pathlet that is slightly different from the original one. A pathlet \(\pi\) is a tuple \((FID, v_1, v_2, \sigma, \delta)\) where all fields are assigned by vertex \(v_1\): FID is an identifier of the pathlet called forwarding identifier, and is unique at \(v_1\); \(v_1 \in V\) is the start vertex; \(v_2 \in V|v_2 \neq v_1\) is the end vertex; \(\sigma\) is a stack of labels from \(L\) called scope stack, and is a new field introduced to restrict the areas where pathlet \(\pi\) should be propagated; and \(\delta\) is a (possibly empty) set of network destinations (e.g., network prefixes) available at \(v_2\). FIDs are used to distinguish between different pathlets starting at the same vertex \(v_1\) and are exploited by the data plane of \(v_1\) to determine where traffic is to be forwarded. Even pathlets that have the same scope stack and, using different network paths, connect the same pair of vertices, can still be distinguished based on the FID. We assume FIDs are integer numbers.

**Packet forwarding** – Each vertex has to keep forwarding state information to support the operation of the data plane. Since our control plane has to update these information, we now define the forwarding state of a vertex by providing hints about the packet forwarding mechanism, which is the same presented in [1]. In pathlet routing, each data packet carries in a dedicated header a sequence of FIDs; this sequence indicates the pathlets that the packet should be routed along to reach the destination. When a vertex \(u\) receives a packet, it considers the first FID in the sequence contained in its header: this FID, referenced as \(f\) in the following, uniquely identifies a pathlet \(\pi\) that is known at \(u\) and that has \(u\) as start vertex. Now, in the general case pathlet \(\pi\) may lead to an end vertex that is not adjacent to \(u\). Since a pathlet does not contain the detailed specification of the routing path to be taken to reach the end vertex, before forwarding the packet \(u\) has to modify the sequence of FIDs contained in the packet header to insert such specification: \(u\) achieves this by replacing \(f\) with another sequence of FIDs that indicates the pathlets to be used to reach the end vertex of \(\pi\). Therefore, the first part of the forwarding state of \(u\) is a correspondence between each value of the FID and a (possibly empty) sequence of FIDs, which we indicate as \(fids_u(FID)\). At this point, \(u\) has to pick a neighboring vertex to forward the packet to. Since also this information is missing in pathlet \(\pi\), it must be kept locally at vertex \(u\). The second part of the forwarding state of \(u\) is therefore the specification of the next-hop vertex, namely of the vertex that immediately comes after \(u\) along \(\pi\), which we refer to as \(nh_u(FID)\). Both \(fids_u\) and \(nh_u\) are computed by the control plane, as explained in the following section.

**Atomic, crossing, and final pathlets** – We distinguish among three types of pathlets: atomic, crossing, and final. A pathlet \(\pi = (FID, v_1, v_2, \sigma, \delta)\) is called atomic pathlet if its start and end vertices are adjacent on graph \(G\). Atomic pathlets carry in the \(\delta\) field the network destinations possibly available at \(v_2\). They are used to propagate information about the network topology and are propagated only inside the most nested area that contains both \(v_1\) and \(v_2\). To represent the fact that a network link \((v_1, v_2)\) is bidirectional, two atomic pathlets need to be created for that link, one from \(v_1\) to \(v_2\) (created by \(v_1\)) and another from \(v_2\) to \(v_1\) (created by \(v_2\)). Atomic pathlets are always marked by putting the special label \(\bot\) at the end of the scope stack. More formally, an atomic pathlet is such that \((v_1, v_2) \in E\) and \(\exists \sigma \neq (\emptyset) \mid \sigma = \sigma \circ \bot\). Besides serving as a distinguishing mark for atomic pathlets, label \(\bot\) has been introduced to simplify the description of pathlet dissemination mechanisms, because it avoids the need to consider several special cases.

A pathlet \(\pi\) is a crossing pathlet for area \(A_{(l)}\) if its start and end vertices are border vertices for area \(A_{(l)}\). Crossing pathlets always have \(\delta = \emptyset\) and do not contain label \(\bot\) in the scope stack. A pathlet of this type offers vertices outside \(A_{(l)}\) (that is, whose label stack is strictly extended by \(\sigma\)) the possibility to traverse \(A_{(l)}\) without knowing its internal topology: crossing pathlets are therefore one of the fundamental building blocks of our control plane, as they realize the possibility to hide detailed routing information about the interior of an area. Since a vertex can be a border vertex for more than one area, different pathlets with the same start and end vertices can act as crossing pathlets for different areas (they would have different scope stacks and FIDs).

A pathlet \(\pi\) is a final pathlet if it leads to some network destination available at \(v_2\), that is, if \(\delta \neq \emptyset\). Like crossing pathlets, final pathlets do not contain label \(\bot\) in the scope stack. Final pathlets are created by a border vertex \(v_1\) for an area \(A_{(l)}\) to inform vertices outside \(A_{(l)}\) about the possibility to reach a destination vertex \(v_2 \in A_{(l)} \cap D\).

Notice that between two neighboring vertices it is possible to create an atomic, a crossing, and a final pathlet: these pathlets are disseminated independently and have each a different role,
as described above. The type (and, therefore, the role and scope of propagation) of these pathlets can be determined based on the contents of $\delta$ and on the presence of the special label $\bot$ in the scope stack. Since the creation and dissemination mechanisms are very similar for crossing and final pathlets, in the following we detail only those applied to crossing pathlets, assuming that they are the same for final pathlets unless differently stated.

Pathlet creation – We now describe how atomic and crossing pathlets are created at each vertex (similar mechanisms are applied for final pathlets). When we say “create” we mean that a vertex defines these pathlets, assigns to each of them a unique $FID$, and keeps them in a local data structure, as illustrated in Section V. In the following, we also use the term “composition” to refer to the creation of crossing and final pathlets.

Each vertex $u \in V$ creates atomic pathlets $\langle FID, u, v, \sigma \circ (\bot), \delta \rangle$ such that $(u, v) \in E$, $\sigma = S(u) \approx S(v)$, and $\delta$ contains the set of network destinations possibly available at $v_2$. The scope stack $\sigma$ is chosen in such a way to restrict propagation of each atomic pathlet up to the most nested area that contains both $u$ and $v$. These pathlets are used to disseminate information about the physical network topology and act as building blocks for creating crossing and final pathlets. When creating an atomic pathlet, vertex $u$ also updates its forwarding state with

$\text{nh}_v(FID) = v$ and $\text{fids}_v(FID) = \emptyset$. Looking at the example of Fig. 1, $v_4$ creates pathlets $\langle 1, 4, v_5, (0 1 \bot), \emptyset \rangle$, $\langle 2, 4, v_2, (0 1 \bot), \emptyset \rangle$, and $\langle 3, 4, v_6, (0 1 \bot), \emptyset \rangle$ (we assigned FIDs randomly). $v_4$ then sets $\text{nh}_v(1) = v_5$, $\text{nh}_v(2) = v_2$, $\text{nh}_v(3) = v_6$, and $\text{fids}_v(1) = \text{fids}_v(2) = \text{fids}_v(3) = \emptyset$.

Atomic pathlets can be concatenated to create pathlets between non-neighboring vertices. To achieve this, we introduce a set $\text{chains}(\Pi, u, v, \sigma)$ that contains all the possible concatenations of pathlets taken from a set $\Pi$, that start at $u$ and end at $v$, and whose scope stack extends $\sigma$, regardless of $FIDs$ and network destinations. $\text{chains}(\Pi, u, v, \sigma)$ is formally defined as the set of all possible sequences of pathlets in $\Pi$, where each sequence $\langle \pi_1, \pi_2, \ldots, \pi_n \rangle$ is finite, cycle-free, and such that $\pi_i = \langle FID_i, w_i, \delta_i, \sigma_i \rangle$, $\sigma_i \subseteq \sigma_i + 1$, $\langle FID_i + 1, w_i + 1, \delta_i + 1, \sigma_i + 1 \rangle$, and $\sigma_i \subseteq \sigma_i + 1$, with $i \in \{1, \ldots, n-1\}$.

A border vertex $u$ exploits these concatenations to create crossing pathlets, that can be used to traverse the areas that $u$ belongs to as if they consisted of a single link. Although $u$ may be a border vertex for several areas, it creates crossing pathlets only for those areas that $u$’s neighbors are actually interested in traversing. To find out which are these areas, we must consider how $u$ appears to its neighbors: we assume that each neighbor $n$ of $u$ that is not in $A_{S(u)}$ considers $u$ as a member of the least nested area that includes $u$ but not $n$, that is, area $A_{S(u)} \approx S(n)$. For this reason, $u$ creates a set of crossing pathlets for each area $\bar{A} = A_{S(u)} \approx S(n)$: these pathlets start at $u$ and end at any other border vertex $v$ for $\bar{A}$, $v \neq u$. Similarly, $u$ creates final pathlets that start at $u$ and end at any other destination vertex $v \in D \cap \bar{A}$. In the example in Fig. 1, $v_6$ considers $v_2$ as a member of area $A_{(0 1 3)} \approx (0 1 3)$, whereas $v_4$ considers $v_3$ as a member of area $A_{(0 1 3)} \approx (0 1 3)$. For this reason, $v_2$ will create crossing and final pathlets for $A_{(0 1 3)}$ to be offered to $v_6$ and crossing and final pathlets for $A_{(0 1 3)}$ to be offered to $v_4$.

More formally, for each neighbor $n$, a border vertex $u \in A_{\sigma}$ creates crossing pathlets by populating a set $\text{crossing}_u(\Pi, \sigma)$, with $\sigma = S(u) \rightarrow S(n)$. Each set $\text{crossing}_u(\Pi, \sigma)$ contains a pathlet $\pi = \langle FID, u, v, \sigma, \delta \rangle$ for each border vertex $v \neq u$ for $A_{\sigma}$ and for each sequence $(\pi_1, \pi_2, \ldots, \pi_n)$ in $\text{chains}(\Pi, u, v, \sigma)$. $\Pi$ is chosen in such a way to be unique at $u$ and $\delta$ is set to the empty set $\emptyset$. Assuming that $\pi_1 = \langle FID_1, u_1, v_1, \sigma_1, \delta_1 \rangle$, the forwarding state of $u$ is updated by setting $\text{fids}_u(FID) = \langle FID_2, FID_3, \ldots, FID_n \rangle$ and $\text{nh}_u(FID) = \text{nh}_u(FID_1) = v_1$. Note that, in general, pathlet $\pi_1$ may not be an atomic pathlet: in this case, $u$ has to recursively expand $\pi_1$ into the component atomic pathlets in order to get the correct sequence of $FIDs$ to be put in $\text{fids}_u(FID)$ and the correct next-hop to be assigned as $\text{nh}_u(FID)$. However, of the way in which set $\text{chains}(\Pi, u, v, \sigma)$ will be used in the following, and in particular because of the composition of set $\Pi$ on which it will be constructed, we assume without loss of generality that $\pi_1$ is always an atomic pathlet. As an example taken from Fig. 1, let $\Pi = \{ (2, v_2, v_4, (0 1 \bot), \emptyset), (3, v_2, v_5, (0 1 \bot), \emptyset), (1, v_1, v_3, (0 1 3 \bot), \emptyset), (2, v_3, v_5, (0 1 \bot), \emptyset) \}$. $v_2$ may have in its set $\text{crossing}_v(\Pi, (0 1))$ a pathlet $\langle 1, v_2, v_3, (0 1) \rangle$ corresponding to the sequence of atomic pathlets $\langle 2, v_2, v_4, (0 1 \bot), \emptyset \rangle$, $\langle 3, v_4, v_5, (0 1 \bot), \emptyset \rangle$ taken from set $\text{chains}(\Pi, v_2, v_5, (0 1))$. $v_2$ will therefore set $\text{fids}_v(1) = (3)$ and $\text{nh}_v(3) = (1)$. Final pathlets are created in a much similar way as crossing pathlets, except that they are composed towards vertices in $A_{\sigma} \cap D$ and $\delta$ is set to the set $\delta$, of network destinations of the last component pathlet in the sequence. Final pathlets are put in a set $\text{final}_u(\Pi, \sigma)$.

Because of the way in which pathlets are created and of the fact that there are no crossing or final pathlets for area $A_{(l_0)}$ (Property 3.2), we can easily conclude that there are always at least two labels in the scope stack of any pathlet. This is stated by the following property:

Property 4.1: For any pathlet $\langle FID, u, v, \sigma, \delta \rangle$ there exists $\sigma \neq ()$ such that $\sigma = (l_0) \circ \sigma$.

Discovery of border vertices – In order to be able to compose crossing pathlets for an area, a border vertex $u$ must be able to discover which are the other border vertices for the same area. The only information that $u$ can exploit to this purpose are the pathlets it has received. Given that a border vertex connects the inner part of an area with vertices outside that area, a simple technique to detect whether a vertex $v$ is a border vertex consists therefore in comparing the scope stacks of suitable pairs of pathlets that have $v$ as a common vertex.

The technique is based on the following lemma.

Lemma 4.1: If a vertex $u \in A_{\sigma}$ receives two
Following simple algorithm, formalized as function \(D\):

1: \textbf{function} DISCOVERBORDERVERTICES\((u, \sigma, \Pi)\)
2: \hspace{1em} \(B \leftarrow \emptyset\)
3: \hspace{1em} for each pair \((\pi_1, \pi_2)\) of pathlets with \(\pi_1 = (FID_1, v_1, w_1, \sigma_1, \delta_1)\) and \(\pi_2 = (FID_2, v_2, w_2, \sigma_2, \delta_2)\), such that \(v_1 \neq v_2 \) or \(w_1 \neq w_2\), and \(\exists v\) such that both \(\pi_1\) and \(\pi_2\) start or end at \(v\) do
4: \hspace{2em} if \(\exists \bar{\sigma}_1 \neq ()\) such that \(\sigma_1 = \bar{\sigma}_1 \circ (l), l \in L\), and \(\exists \bar{\sigma}_2 \neq ()\) such that \(\sigma_2 = \bar{\sigma}_2 \circ (\bot)\) and \(\sigma_1 = \sigma\) and \(\sigma_2 \sqsubseteq \sigma\) then
5: \hspace{3em} \(B \leftarrow B \cup \{v\}\)
6: \hspace{1em} end if
7: \hspace{1em} end for
8: \hspace{1em} return \(B\)
9: \textbf{end function}

pathlets \(\pi_1 = (FID_1, v_1, w_1, \sigma_1, \delta_1)\) and \(\pi_2 = (FID_2, v_2, w_2, \sigma_2, \delta_2)\), with \(l \in L\), \(\sigma_1 \neq ()\), \(\sigma_2 \neq ()\), the start and end vertices of \(\pi_1\) and \(\pi_2\) are such that \(v_1 \neq v_2\) or \(w_1 \neq w_2\), the scope stacks of \(\pi_1\) and \(\pi_2\) are such that \(\sigma_2 \sqsubseteq \sigma = \sigma_1\), and there exists a vertex \(v\) such that both \(\pi_1\) and \(\pi_2\) start or end at \(v\), then \(v\) is a border vertex for \(A_\sigma\).

\textbf{Proof:} The statement follows from the way in which scope stacks are assigned to pathlets. The fact that \(v \in \{v_1, w_1\}\) implies that \(v \in A_\sigma\); in fact, if \(l = \bot\), then \(\pi_1\) is an atomic pathlet whose scope stack is therefore assigned in such a way that \(\sigma_1 = S(v_1) \times S(w_1)\); since we know that \(S(v_1) \times S(w_1) \subseteq S(v)\), by Property 3.1 we can conclude that \(v \in A_\sigma\). Otherwise, if \(l \neq \bot\), then \(\pi_1\) is either a crossing pathlet for some area \(A_{\sigma_1(l)}\) or a final pathlet; in both cases, being an endpoint of pathlet \(\pi_1, v\) must belong to \(A_{\sigma_1(l)}\) and, using Property 3.1 again, this also implies that \(v \in A_{\sigma_1}\). Since \(\sigma_1 = \sigma\), we can conclude that \(v \in A_\sigma\). On the other hand, from the scope stack \(\sigma_2 \sqsubseteq \sigma\) of the atomic pathlet \(\pi_2\) we know that \(v\) has some neighbor that is not in \(A_\sigma\); this makes \(v\) a border vertex for \(A_\sigma\).

According to this lemma, a vertex \(u \in A_\sigma\) can use the following simple algorithm, formalized as function DISCOVERBORDERVERTICES\((u, \sigma, \Pi)\) in Algorithm 1, to discover other border vertices for \(A_\sigma\) based on a set of known pathlets \(\Pi\): consider any possible pair \((\pi_1, \pi_2)\) of pathlets in \(\Pi\) whose start and end vertices have exactly one vertex \(v\) in common; if this pair satisfies the conditions of the lemma, \(v\) is a border vertex for \(A_\sigma\).

\textbf{Routing policies} – So far we have described how to compose crossing and final pathlets by considering all the possible concatenations of available pathlets. Although this produces the highest possible number of alternative paths, resulting in the best level of robustness and in the availability of different levels of Quality of Service, depending on the topology and on the assignment of areas it can be demanding in terms of messages exchanged on the network and of pathlets kept at each router. However, our control plane can also easily accommodate routing policies that influence the way in which pathlets are composed and disseminated. We stress that these policies can be implemented independently for each area: that is, the configuration of routing policies on the internal vertices of an area may have no impact on the routing information propagated outside that area. We believe this is a significant relief for network administrators, who do not necessarily need any longer to keep a complete knowledge of the network setup and to perform a complex planning of configuration changes.

We envision two kinds of policies: filters and pathlet composition rules. Filters can be used to restrict the propagation of pathlets. For example, the specification of a filter on a vertex \(u\) can consist of a neighboring vertex \(v\) and a triple \(\langle w_1, w_2, \sigma \rangle\): when such a filter is applied, \(u\) will avoid propagating to \(v\) all those pathlets whose start vertex, end vertex, and scope stack match the triple. Pathlet composition rules can be used to affect the creation of crossing and final pathlets. We describe here a few possible pathlet composition rules. As opposed to the strategy of considering all the possible concatenations of pathlets, a border vertex \(v\) can create, for each end vertex \(w\) of interest, only one crossing (or final) pathlet that corresponds to an optimal sequence of pathlets to that end vertex. Several optimality criteria can be pursued. For example, \(v\) could select the shortest sequence of pathlets by running Dijkstra’s algorithm on the graph resulting by the union of the pathlets it knows. We highlight that, with this approach, \(v\) can still keep track of possible alternative paths but does not propagate them as pathlets: in case the shortest sequence of pathlets to a certain vertex \(w\) is no longer available (for example because of a failure), \(v\) can transparently switch to an alternative sequence of pathlets leading to \(w\) by just updating the forwarding state and without sending any messages outside its area \(A_{\sigma(v)}\).

As a variant of this approach, pathlets can be weighted according to performance indicators (delay, packet loss, jitter) of the network portion they traverse: in this case the optimal sequence of pathlets corresponds to the one offering the best performance. Alternatively, pathlets can be weighted according to their nature of atomic or crossing pathlet: assuming that atomic pathlets are assigned weight 0 and crossing pathlets are assigned weight 1, the optimal pathlet tries to avoid transit through areas. Another pathlet composition rule could accommodate the requirement of an administrator that wants to prevent traffic from a specific set \(\overline{V}\) of vertices from traversing a specific area \(A\). Since detailed routing information about the interior of an area is not propagated outside that area, it may not be possible to establish whether a specific pathlet traverses \(A\) or not. Therefore, to implement this pathlet composition rule, pathlets could carry an additional attribute that is a set of shaded vertices: crossing pathlets for \(A\) disseminated by the border vertices of \(A\) will have the set of shaded vertices set to \(\overline{V}\); upon receiving a pathlet, a vertex \(v\) will check whether \(v\)’s identifier appers in the set of shaded vertices and, if so, will refrain from using that pathlet for composition or for sending traffic. A similar mechanism could be implemented to prevent traffic to specific destinations from traversing \(A\):
in this case, a set of shaded destinations could be carried in the pathlets instead. Of course, the two techniques can be combined by using both the set of shaded vertices and the set of shaded destinations: in this way, a set of vertices V can be prevented from traversing an area A to send traffic to specific destinations.

**Pathlet dissemination** – All the created pathlets are disseminated to other vertices in G based on their scope stacks, as explained in the following. Consider any pathlet \( \pi = (FID, u, v, \sigma, \delta) \) and let \( \sigma = \tilde{\sigma} \circ (l) \) (by Property 4.1, such \( \tilde{\sigma} \neq () \) and \( l \in L \) must exist). The dissemination of \( \pi \) is regulated by the following propagation conditions. A vertex \( w \) can propagate \( \pi \) to a neighboring vertex \( n \) either if \( n = u \) or if \( \pi \)'s scope stack does not satisfy any of the following conditions:

1. \( S(w) \preceq S(n) \cap \tilde{\sigma} \): restricts propagation of any pathlets outside the area in which they have been created;
2. \( \sigma \subseteq S(w) \preceq S(n) \): prevents propagation of crossing and final pathlets inside the area of the vertex that created them;
3. \( \sigma = S(n) \rightarrow S(w) \): prevents \( w \notin A \) from propagating crossing and final pathlets for \( A \) inside \( A \);
4. \( n = v \): prevents sending to \( n \) a pathlet that is useless for \( n \).

Conditions 2), 3), and 4) are introduced to prevent the propagation of pathlets to vertices that would never use them, thus limiting the amount of exchanged information during pathlet dissemination. Condition 1) can be expressed from the point of view of a single vertex, leading to the following invariant:

**Property 4.2:** All the pathlets received by a vertex \( v \) have a scope stack \( \sigma' = \tilde{\sigma} \circ (l) \) such that \( \tilde{\sigma} \subseteq S(v) \).

For convenience, given a vertex \( w \) that is assigned scope stack \( S(w) = \sigma_w \), we define \( N(w, \sigma_w, \sigma) \) as the set of neighbors of \( w \) to which \( w \) can propagate a pathlet with scope stack \( \sigma \) according to the propagation conditions and to the routing policies. We assume that \( N(w, \sigma_w, ()) = \emptyset \) for any \( \sigma_w \).

So far we have mentioned that the propagation conditions regulate the propagation of pathlets. However, we will see in Section V that other kinds of messages exchanged by our control plane are also propagated according to the same conditions.

**Example of pathlet creation and dissemination** – To show a complete example of creation and dissemination of pathlets, consider again the example in Fig. 1 and let \( v_6 \) host network destination \( d \). In the following we assume that there are no filters applied, that the pathlet composition rule is to compose all possible sequences of pathlets (although we show only some of them), and that FIDs are randomly assigned integer numbers, yet obeying the rules specified in this section. The atomic pathlet \( \pi_{24,\perp} = (1, v_2, v_4, (0 1 \perp), \emptyset) \), created by vertex \( v_2 \), is propagated by \( v_2 \) to \( v_3 \) because \( S(v_2) \preceq S(v_3) = (0 1 3) \notin (0 1), (0 1 \perp) \notin (0 1 3), (0 1 \perp) \neq S(v_3) \rightarrow S(v_2) = (0 1 3) \), and \( v_3 \neq v_4 \); it is also propagated to \( v_1 \) for the same reasons. Instead, \( \pi_{24,\perp} \) is not propagated by \( v_2 \) to \( v_6 \) because \( S(v_2) \preceq S(v_6) = (0) \subsetneq (0 1) \) (the first propagation condition applies), and it is not propagated by \( v_2 \) to \( v_4 \) because the end vertex of \( \pi_{24,\perp} \) is \( v_4 \) itself. For similar reasons, \( \pi_{24,\perp} \) is further propagated by \( v_3 \) to \( v_5 \), but in turn \( v_5 \) does not propagate it to \( v_7 \). Therefore, the visibility of \( \pi_{24,\perp} \) is restricted to vertices inside \( A(0 1) \). In a similar way, \( v_5 \) creates the atomic pathlets \( \pi_{53,\perp} = (2, v_5, v_3, (0 1 \perp), \emptyset) \) and \( \pi_{54,\perp} = (3, v_5, v_4, (0 1 \perp), \emptyset) \), while \( v_4 \) creates the atomic pathlet \( \pi_{46,\perp} = (3, v_4, v_6, (0 \perp), (d)) \). The reader can easily find how these atomic pathlets are propagated. As a border vertex of \( A(0 1 3) \), \( v_5 \) will also propagate to \( v_5 \) the crossing pathlet \( \pi_{32} = (1, v_3, v_4, (0 1 3), \emptyset) \) for area \( A_S(v_3) \rightarrow S(v_5) = (0 1 3) \). Once pathlets have been disseminated, \( v_5 \) has learned about a set of pathlets \( P \) and can create a crossing pathlet for area \( A_S(v_3) \rightarrow S(v_5) = (0 1 3) \) that can be offered to \( v_7 \). For example, \( v_5 \) can pick sequence \( (1, v_3, v_4, (0 1 3), \emptyset) \) to construct a path from itself to vertex \( v_6 \), which contains destination \( d \); it can concatenate pathlets \( \pi_{53,\perp}, \pi_{54,\perp} \), and \( \pi_{46,\perp} \) or pathlets \( \pi_{24,\perp}, \pi_{54,\perp} \), and \( \pi_{46,\perp} \). The availability of multiple choices supports quick recovery in case of fault and allows \( v_7 \) to select the pathlet providing the most appropriate Quality of Service.

**V. A CONTROL PLANE FOR PATHLET ROUTING:**

**MESSAGES AND ALGORITHMS**

We now describe how the dissemination mechanisms illustrated in Section IV are realized in terms of messages exchanged among vertices and algorithms executed to update routing information. In this section we also detail how to handle network dynamics, including how to deal with topological changes and administrative reconfigurations. This actually completes the specification of a control plane for pathlet routing.

**A. Message Types**

First of all, we detail all the messages that are used by vertices to disseminate routing information. Each message carries one or more of the following fields: \( s \): a stack of labels; \( d \): a set of network destinations; \( p \): a pathlet; \( FID \): a FID; \( o \): a boolean flag (which tells whether a vertex has “just been activated”). We assume that every message includes an **origin** field \( o \) that specifies the vertex that first originated the
message. Messages can be of the following types, with their fields specified in square brackets:

- **Hello** \([s, d, a]\) – Used for neighbor greetings. It carries the label stack \(s\) of the sender vertex, the set of network destinations \(d\) originated by the sender vertex, and a flag \(a\) which is set to true when this is the first message sent by a vertex since its activation (power-on or reboot). Unlike other message types, **Hello** is only sent to neighbors and is never forwarded. Moreover, in order to be able to detect topological variations, it is sent periodically by each vertex.

- **Pathlet** \([p]\) – Used to disseminate a pathlet \(p\).

- **Withdrawlet** \([f, s]\) – Used to withdraw the availability of a pathlet with FID \(f\), scope stack \(s\), and start vertex \(o\). We assume that this message can only be originated by the vertex that had previously created and disseminated the pathlet.

- **Withdraw** \([s]\) – Used to withdraw the availability of all pathlets having \(s\) as scope stack and \(o\) as start vertex.

In order to keep disseminated information consistent in the presence of faults and reconfigurations, we assume for convenience that all vertices in the network have a synchronized clock, and we call \(T\) its value at any time. Every message type but **Hello** has a **timestamp** field \(t\) that, unless otherwise stated, is set by the sender to the current clock \(T\) when sending a newly created message; the timestamp is left unchanged when a message is just forwarded from a vertex to another. The purpose of the timestamp is to let vertices discard outdated messages, which is especially important in the presence of faults. In practice, a local counter at each vertex can be used in place of the clock value, and its value can be handled in a way similar to OSPF sequence numbers (see in particular Section 12.1.6 of [14]).

With the exception of **Hello**, messages also have a **source** field \(src\) containing the identifier of the vertex that has sent (or forwarded) the message. This field is also used to avoid sending the message back to the vertex from which it has been received (a technique similar to the split horizon adopted in commercial routers). Since the **Hello** message is never forwarded by any vertices, it contains only the origin field.

Given their particular nature, in the following we omit specifying for each message how the origin, timestamp, and source fields are set, unless we need exceptions to their usual assignment.

**B. Routing information stored at each vertex**

In our control plane, no vertex has a complete view of all the available routing paths. However, as a partial representation of the current network status, each vertex \(u \in V\) keeps the following information locally:

- For each neighbor \(v \in V\) such that \((u, v) \in E\), a label stack \(S_u(v)\) that \(u\) currently considers associated with \(v\) and a set \(D_u(v)\) of network destinations originated by \(v\).

- A set \(\Pi_u\) of **known pathlets**, consisting of the atomic pathlets created by \(u\) and of pathlets that \(u\) has received from neighboring vertices. \(u\) can concatenate these pathlets to reach network destinations and, in case it is a border vertex, to compose and disseminate crossing and final pathlets. Each pathlet \(\pi \in \Pi_u\) is associated an expiry timer \(T_p(\pi)\), that specifies how long the pathlet is to be kept in \(\Pi_u\) before being removed. When a new pathlet is created by \(u\), its expiry timer is set to the special value \(T_p(\pi) = \emptyset\), meaning that the pathlet never expires.

- For every area \(A_u\) for which \(u\) is a border vertex, a set \(B_u(\sigma)\) of vertices \(v \in A_u\), \(v \neq u\); that are also border vertices for \(A_u\), and sets \(C_u(\sigma)\) and \(F_u(\sigma)\) that contain, respectively, the crossing and final pathlets for area \(A_u\) composed by \(u\).

- A set \(H_u\), called **history**, that tracks the most recent piece of information known by \(u\) about each pathlet (i.e., not just pathlets in \(\Pi_u\)). This set consists of tuples \((FID, v, \sigma, t, type)\), where: the FID and the start vertex \(v\) identify a pathlet \(\pi\) with scope stack \(\sigma\); \(t\) is the timestamp of the most recent information that \(u\) knows about \(\pi\) (it may be the time instant of when \(\pi\) has been composed or deleted by \(u\), or the timestamp contained in the most recent message received by \(u\) about \(\pi\)); and \(type \in \{+, -\}\) determines whether the last known information about \(\pi\) is positive (\(\pi\) has been composed by \(u\) or a **Pathlet** message has been received about \(\pi\)) or negative (\(\pi\) has been deleted by \(u\) or a **Withdrawlet** or **Withdraw** message has been received about \(\pi\)).

The reason why we have introduced an expiry timer \(T_p(\pi)\) for each pathlet \(\pi\) in \(\Pi_u\) is that we want to prevent indefinite growth of \(\Pi_u\). In fact, there may be pathlets that can no longer be used by \(u\) for concatenations and for which \(u\) may never receive a **Withdrawlet** or **Withdraw** message: the expiry timer is used to automatically purge such pathlets from \(\Pi_u\). This situation can occur when a vertex or a link is removed from \(G\). For example, consider the network in Fig. 1 and suppose that \(v_2\) composes and announces a crossing pathlet \(\pi_{25} = \langle 7, v_2, v_5, (0.1), \emptyset \rangle\) for area \(A_{(0.1)}\). If link \((v_2, v_5)\) fails, \(v_4\) has no way to receive a **Withdrawlet** for \(\pi_{25}\), because only \(v_2\) can originate this message and the propagation conditions prevent it from being forwarded inside area \(A_{(0.1)}\). However, \(v_6\) can no longer use \(\pi_{25}\) for any concatenations and therefore has no reason to keep this pathlet in its set \(\Pi_{v_6}\); \(\pi_{25}\) can indeed be automatically removed after timer \(T_p(\pi_{25})\) has expired. The configuration of our control plane therefore requires the specification of a timeout value called **pathlet timeout**: this is the value to which the expiry timer \(T_p(\pi)\) of a pathlet \(\pi\) is initialized when \(T_p(\pi)\) is activated (we will see in the following when this activation occurs).

Also the history \(H_u\) could grow indefinitely, because an entry is stored and kept in \(H_u\) even for each deleted or withdrawn pathlet. Therefore, our control plane also requires the specification of a **history timeout**: this value determines how long negative entries (i.e., with \(type = -\)) in the history \(H_u\) of any vertex \(u\) are kept before being automatically purged from \(H_u\). Positive entries (with \(type = +\)), on the other hand,
never expire.

In principle, we could completely avoid timeouts and remove pathlets and history entries immediately. However, this would significantly increase the number of exchanged messages and cause the deletion of pathlets that should instead be preserved, even in normal operational conditions. Consider again Fig. 1 and assume there is no pathlet expiry timer. If \(v_6\) received only pathlet \(\pi_{57, \perp} = (6, v_5, v_7, (0 \perp), \emptyset)\) before receiving the crossing pathlet \(\pi_{25, \perp}\), it would immediately withdraw \(\pi_{57, \perp}\) because it cannot use it for concatenations and it may never receive a Withdraw or Withdrawlet for that pathlet. A similar argument applies to the history timer. Look back at Fig. 1 and assume there is no history expiry timer. Note that with this assumption negative entries are just not kept in the history, actually defeating its purpose. Suppose that, after disseminating an atomic pathlet \(\pi_{62, \perp} = (1, v_6, v_2, (0 \perp), \emptyset)\) to the whole network, vertex \(v_6\) withdraws this pathlet using a Withdrawlet message (for example because the link to the whole network, vertex \(v\), is cut). For the sake of clarity, we specify here the strategy with which the history is updated when creating or deleting pathlets, and avoid mentioning it again, unless there are exceptions to this strategy. Every time a pathlet \(\pi = (\text{FID}, u, v, \sigma, \delta)\) is created by a vertex \(u\), the history \(H_u\) of \(u\) is automatically updated with a positive entry \((\text{FID}, u, \sigma, T, +)\), where \(T\) denotes the time instant of the creation. If an entry for the same \(\text{FID}\) and start vertex \(u\) already existed in \(H_u\), that entry is replaced by this updated version. When pathlet \(\pi\) is no longer available (for example because \(u\) has detected that some of the component pathlets are no longer usable), \(H_u\) is updated with a negative entry \((\text{FID}, u, \sigma, T, -)\), where \(T\) denotes the time instant in which \(\pi\) has become unavailable. This entry replaces any previously existing entry referring to the same pathlet \(\pi\). We recall that this negative entry is automatically removed from \(H_u\) after the history timeout expires.

C. Algorithms to Support Handling of Network Dynamics

Before actually describing how network dynamics are handled, we introduce a few algorithms that vertices execute when they detect a change of the locally maintained routing information. In particular, we describe the operations performed by a vertex \(u\) when its set of known pathlets \(\Pi_u\), \(C_u\), or \(F_u\) are updated. Most of the events that may trigger such updates, including topological changes and administrative reconfigurations, can be handled based on the algorithms described in this subsection. We discuss in detail the application of these algorithms to handle specific events in the following subsections.

Suppose the set \(\Pi_u\) of currently known pathlets at a vertex \(u\) is changed and is to be replaced by a new set of known pathlets \(\Pi_{new, u}\). \(u\) then undertakes the following actions, formalized as procedure \textsc{UpdateKnownPathlets}(\(u, \Pi_{new, u}\)) in Algorithm 2: \(u\) sends messages to its neighbors to disseminate pathlets that are newly appeared in \(\Pi_{new, u}\) and withdraw those that are no longer in this set. Note that, while withdrawn pathlets are immediately removed from \(\Pi_u\) at the end of the algorithm, the corresponding forwarding state is only cleared by \(u\) after a timeout \(T_f\), in order to allow correct forwarding of data packets while the withdraw is propagated on the network (note that the statement at line 28 of Algorithm 2 is non-blocking). Of course some packets could be lost if the withdrawn pathlets are physically unavailable.

Pathlets that existed in \(\Pi_u\) but have their scope stack or set of destinations updated in \(\Pi_{new, u}\) are handled by \(u\) in a special way: for each of these pathlets \(u\) disseminates the updated instance of the pathlet to selected neighbors (according to the propagation conditions and to the routing policies set at \(u\)), and withdraws the old instance of the pathlet from other neighbors to which the new instance of the pathlet cannot be disseminated. After having updated \(\Pi_u\) with the contents of \(\Pi_{new, u}\), \(u\) checks whether the start vertex of each pathlet in \(\Pi_u\) is still reachable: it does so by concatenating arbitrary pathlets in \(\Pi_u\), regardless of their scope stacks. If the start vertex of some pathlet \(\pi\) is found to be unreachable, or if including \(\pi\) in any sequences of pathlets would always result in a cycle, \(u\) can no longer use pathlet \(\pi\) for composition or traffic forwarding, and it schedules automated deletion of the pathlet from \(\Pi_u\) by initializizing its expiry timer \(T_p(\pi)\). For all the other pathlets, the expiry timer is reset, meaning that they will never expire. Last, \(u\) checks whether the component pathlets of its crossing and final pathlets are still available and whether new crossing or final pathlets can be composed, and updates sets \(C_u\) and \(F_u\) accordingly. The latter step requires further actions, which are detailed in the following procedure.

When set \(\Pi_u\) is replaced by \(\Pi_{new, u}\), vertex \(u\) must also check whether the component pathlets for its crossing and final pathlets are still available in \(\Pi_{new, u}\) and whether there are new crossing and final pathlets that \(u\) should compose due to newly appereded pathlets in \(\Pi_{new, u}\). Function \textsc{IsPathletComposable}(\(u, \pi, \Pi, E\)) in Algorithm 3 can be used to establish whether a certain pathlet \(\pi\) can (still) be composed by \(u\) based on the set \(\Pi\) of known pathlets at \(u\) and on a set \(E\) of admissible end vertices for \(\pi\) (the check performed by this function actually reflects the mechanism for the construction of set crossing, as explained in Section IV). The composition (or deletion) of crossing and final pathlets also depends on the areas for which \(u\) is a border vertex and on the knowledge of other border vertices. All the operations that \(u\) is supposed to execute to update its crossing and final pathlets are therefore formalized as procedure \textsc{UpdateComposedPathlets}(\(u, \Pi_{new, u}\)) in Algorithm 4: \(u\) considers pathlets that it can no longer compose \((C_{old})\) because it is no longer a border vertex for some area or because some of the component pathlets are no longer available in \(\Pi_{new, u}\); \(u\) may also compose new crossing and final pathlets \((C_{new})\) because it has become a border vertex for some area or because there are new possible compositions of pathlets.
Algorithm 2 Algorithm to update the set $\Pi_u$ of known pathlets at a vertex $u$. The first procedure addresses the case when the label stack of $u$ is contextually changed from $S_{old}$ to $S_{new}$, whereas the second only realizes the update of $\Pi_u$.

1: procedure UPDATEKNOWNPATHLETSANDSTACK($u$, $S_{old}$, $S_{new}$, $\Pi_{new}$)
2: for each $\pi = (FID, v, w, \sigma, \delta) \in \Pi_{new} \setminus \Pi_u$ do
3: We are considering a pathlet $\pi$ that is not in $\Pi_u$ but is in $\Pi_{new}$ (new pathlet) or the updated instance of a pathlet that is both in $\Pi_u$ and in $\Pi_{new}$
4: if $u = v$ then
5: Update $u$’s forwarding state according to the composition of $\pi$
6: $M \leftarrow$ new Pathlet message
7: $M.p \leftarrow \pi$
8: for each $n \in N(u, S_{new}, \sigma)$ do
9: Send $M$ to neighbor $n$
10: end for
11: end if
12: end for
13: for each $\pi_{old} = (FID, v, w, \sigma_{old}, \delta_{old}) \in \Pi_u \setminus \Pi_{new}$ do
14: if $u = v$ then
15: $M \leftarrow$ new Withdrawlet message
16: $M.p \leftarrow FID$
17: $M.n \leftarrow \sigma_{old}$
18: if $\exists_{new} = (FID, v, w, \sigma_{new}, \delta_{new}) \in \Pi_{new}$ then
19: We are considering a pathlet $\pi_{old}$ that is in $\Pi_u$ and has an updated instance $\pi_{new}$ in $\Pi_{new}$
20: for each $n \in N(u, S_{old}, \sigma_{old}) \setminus N(u, S_{new}, \sigma_{new})$ do
21: Send $M$ to neighbor $n$
22: end for
23: else
24: We are considering a pathlet $\pi_{old}$ that is in $\Pi_u$ but has been removed in $\Pi_{new}$
25: for each $n \in N(u, S_{old}, \sigma_{old})$ do
26: Send $M$ to neighbor $n$
27: end for
28: Clear $fids_u(FID)$ and $nh_u(FID)$ after a timeout $T_f$
29: end if
30: end if
31: end for
32: $\Pi_u \leftarrow \Pi_{new}$
33: for each $\pi = (FID, v, w, \sigma, \delta) \in \Pi_u$ do
34: if $v \in E$ and $\exists (\pi_1, \pi_2, \ldots, \pi_n) \in chains(\Pi_u, u, v, \sigma)$ such that $\pi_i = (FID_i, u_i, v_i, \sigma_i, \delta_i), i = 1, \ldots, n$ and $fids_u(FID) = (FID_2 FID_3 \ldots FID_n)$ and $nh_u(FID) = u_2$ and the pathlet composition rules allow composition of $\pi$ then
35: $T_p(\pi) \leftarrow$ value of the pathlet timeout parameter
36: else
37: $T_p(\pi) \leftarrow \infty$
38: end if
39: end for
40: UPDATECOMPOSEDPATHLETSANDSTACK($u$, $S_{old}$, $S_{new}$, $\Pi_u$)
41: end procedure
42: procedure UPDATEKNOWNPATHLETS($u$, $\Pi_{new}$)
43: UPDATEKNOWNPATHLETSANDSTACK($u$, $S(u)$, $S(u)$, $\Pi_{new}$)
44: end procedure

Algorithm 3 Algorithm to check whether a pathlet $\pi$ can (still) be composed by a vertex $u$ given a set $\Pi$ of known pathlets and a set $E$ of admissible end vertices for $\pi$.

1: function ISPATHLETCOMPOSABLE($u$, $\pi$, $\Pi$, $E$)
2: Let $\pi = (FID, u, v, \sigma, \delta)$
3: if $v \in E$ and $\exists (\pi_1, \pi_2, \ldots, \pi_n) \in chains(\Pi, u, v, \sigma)$ such that $\pi_i = (FID_i, u_i, v_i, \sigma_i, \delta_i), i = 1, \ldots, n$ and $fids_u(FID) = (FID_2 FID_3 \ldots FID_n)$ and $nh_u(FID) = u_2$ and the pathlet composition rules allow composition of $\pi$ then
4: return True
5: else
6: return False
7: end if
8: end function

In $\Pi_{new}$, if possible, $u$ attempts to transparently replace pathlets in $C_{old}$ with newly composed pathlets from $C_{new}$ by just updating its forwarding state and without sending any messages; if this is not possible, $u$ withdraws the no longer available pathlets from those neighbors to which they had been disseminated and clears the forwarding state for these pathlets after a timeout $T_f$ (the statement at line 41 of Algorithm 4 is non-blocking). Last, $u$ disseminates to selected neighbors (according to the propagation conditions and the routing policies) all those newly composed pathlets in $C_{new}$ that were not used as a replacement for pathlets in $C_{old}$. Pathlet composition at line 12 of Algorithm 4 is the same mechanism as for set $cP$: we did not use set $crossing(\Pi_{new}, \sigma)$ here because the FIDs of already existing
Algorithm 4 Algorithm to update the sets of crossing and final pathlets composed by a vertex $u$. The first procedure considers the case when the label stack of $u$ is contextually changed from $S_{old}$ to $S_{new}$, whereas the second only realizes the update of crossing and final pathlets.

1: procedure UPDATECOMPOSEDPATHLETSANDSTACK($u, S_{old}, S_{new}, \Pi_{new}$)
2:  for each area $A_o$ do
3:    $C_{new} \leftarrow \emptyset$
4:    $C_{old} \leftarrow \emptyset$
5:    if $u$ is a border vertex for $A_o$ then
6:      $B_o(\sigma) \leftarrow \text{DISCOVERBORDERVERTICES}(u, \sigma, \Pi_{new})$
7:    if $C_u(\sigma) = \emptyset$ then
8:      Vertex $u$ has become a border vertex for $A_o$ or has not yet composed any pathlets for that area; pathlets in set $\text{crossing}_u(\Pi_{new}, \sigma)$ below have end vertices in $B_o(\sigma)$
9:      $C_{new} \leftarrow \text{crossing}_u(\Pi_{new}, \sigma)$
10:    else
11:      Vertex $u$ continues to be a border vertex for $A_o$, but it has to refresh available crossing pathlets according to the contents of $\Pi_{new}$
12:      $C_{new} \leftarrow \text{new crossing pathlets not in } C_u(\sigma)$, that $u$ can compose towards vertices in $B_o(\sigma)$ using pathlets in $\Pi_{new}$ and according to the pathlet composition rules
13:      $C_{old} \leftarrow \{ \pi | \pi \in C_u(\sigma) \text{ and not ISPATHLETCOMPOSABLE}(u, \pi, \Pi_{new}, B_o(\sigma)) \}$
14:    end if
15:    else if $C_u(\sigma) \neq \emptyset$ then
16:      Vertex $u$ was a border vertex for $A_o$ but is no longer
17:      $C_{old} \leftarrow C_u(\sigma)$
18:    end if
19:    Update $u$’s forwarding state for any pathlet in $C_{new}$
20:    if $C_{old} = C_u(\sigma)$ then
21:      All the crossing pathlets have been removed: this piece of information can be propagated with a single Withdraw message
22:      $M \leftarrow$ a new Withdraw message
23:      $M.\_S \leftarrow \sigma$
24:      for each $n \in N(u, S_{old}, \sigma)$ do
25:        Send $M$ to neighbor $n$
26:      end for
27:    else
28:      for each $\pi_{old} = (\text{FID}_{old}, v, w, \sigma, \delta) \in C_{old}$ do
29:        if $\exists \pi_{new} = (\text{FID}_{new}, v, w, \sigma, \delta) \in C_{new}\backslash C_{old}$ then
30:          Use an alternative pathlet $\pi_{new}$ to transparently replace a no longer available pathlet $\pi_{old}$ by only updating $u$’s forwarding state
31:            $\text{fids}_u(\text{FID}_{old}) \leftarrow \text{fids}_u(\text{FID}_{new})$
32:            $\text{nh}_u(\text{FID}_{old}) \leftarrow \text{nh}_u(\text{FID}_{new})$
33:            $C_{new} \leftarrow (C_{new}\backslash \{\pi_{new}\}) \cup \{\pi_{old}\}$
34:        end if
35:      end for
36:      $M \leftarrow$ a new Withdrawlet message
37:      $M.\_S \leftarrow \sigma$
38:      for each $n \in N(u, S_{old}, \sigma)$ do
39:        Send $M$ to neighbor $n$
40:      end for
41:    end if
42:  end for
43:
44:  for each $\pi_{new} = (\text{FID}_{new}, v, w, \sigma, \delta) \in C_{new}\backslash C_{old}$ do
45:    $M \leftarrow$ a new Pathlet message
46:    $M.\_P \leftarrow \pi$
47:    for each $n \in N(u, S_{new}, \sigma)$ do
48:      Send $M$ to neighbor $n$
49:    end for
50:  end for
51:  $C_u(\sigma) \leftarrow (C_u(\sigma)\backslash C_{old}) \cup C_{new}$
52: end for
53: end if
54: end for
55: end if
56: procedure UPDATECOMPOSEDPATHLETS($u, \Pi_{new}$)
57:  UPDATECOMPOSEDPATHLETSANDSTACK($u, S(u), S(u), \Pi_{new}$)
58: end procedure
pathlets in $C_u(\sigma)$ must be retained.

D. Handling Topological Variations and Configuration Changes

As soon as a vertex $u$ becomes active on the network, it sends a Hello message $M$ to all its neighbors, with $M.s$ set to its label stack $S(u)$, $M.d$ set to the available destinations at $u$ (if any), and $M.a = \text{TRUE}$. With this simple neighbor greeting mechanism, each vertex can learn about its neighborhood. Once a vertex has collected this information, it starts creating and disseminating atomic pathlets as explained in Section IV. Although this reasonably summarizes the behavior of a vertex that has just appeared on the network, “becoming active” is just one of the possible topological variations that graph $G$ may undergo during network operation. Moreover, our control plane must also support administrative configuration changes that can occur while the network is running.

In our model, most topological variations and configuration changes can be represented as a change of label stacks, in the following way: addition of a link $(u, v)$ is modeled by the assignment of value $S(v)$ to label stack $S_u(v)$ and of value $S(u)$ to label stack $S_u(u)$; removal of a link $(u, v)$ is modeled as a change of label stacks $S_u(v)$ and $S_v(u)$ to the empty stack $\emptyset$; addition and removal of a vertex are modeled as a simultaneous addition or removal of all its incident edges; an administrative configuration change that modifies the label stack $S(v)$ assigned to a vertex $v$ is modeled as an update of stacks $S_u(v)$ of all the neighbors $w$ of $v$. To complete the picture of possible reconfigurations, we assume that a change in the routing policies of a vertex causes a reboot of that vertex (this assumption can be removed, but then each vertex has to keep track of the pathlets it has propagated): we therefore do not discuss this kind of configuration change further. For these reasons, we can handle all relevant network dynamics by defining a generic algorithm to deal with a change of the known label stack of a vertex. We will see in the rest of this section that this algorithm is designed to limit the propagation of the effect of a network change: in fact, only those pathlets that involve vertices affected by the change are disseminated as a consequence of the change. Moreover, we enforce mechanisms to transparently replace a pathlet that is no longer available without the need to disseminate any information to the rest of the network.

In principle, we could define an algorithm for “push” and “pop” primitives on the stack of $v$ and consider a generic stack change as consisting of a suitable sequence of pop operations followed by push operations. However, this choice has two drawbacks: first of all, care should be taken in order to avoid that push and pop operations triggered by different network events are mixed up, resulting in inconsistent assignments of label stacks; second, implementing a stack change as a sequence of push and pop operations results in more messages being exchanged. As an example, consider again the network in Fig. 1 and suppose that vertex $v_2$ has its stack administratively changed from $S(v_2) = (0 \ 1 \ 3)$ to $S(v_2) = (0 \ 2 \ 1)$; if this event were implemented with push and pop primitives, $v_2$ would also be assigned the intermediate stack $(0 \ 1)$, which would make $v_1$ a border vertex for area $A_{(0 \ 1 \ 3)}$ and cause $v_1$ to disseminate appropriate crossing (and final) pathlets for that area. Instead, in the final state in which $S(v_2) = (0 \ 2 \ 1)$, $v_1$ is not supposed to disseminate these pathlets, because it is a border vertex only for area $A_{(0 \ 1)}$. We therefore consider the stack change as an atomic operation in the following.

Stack change – We now describe the operations performed by a vertex when its label stack is administratively changed, for example because the vertex is moved to a different area. Despite being also modeled as a stack change, this does not include the case when the vertex fails, because of course it would not be able to undertake any actions: this case is handled just as if neighbors of the failed vertex received a Hello message from that vertex with $s$ set to $\emptyset$, and is therefore discussed later on.

Consider a vertex $u \in V$ and suppose its label stack $S(u)$ is changed at a certain time instant from $S_{old}$ to $S_{new}$. As a consequence of this change, some pathlets may be created or deleted by $u$, or have their scope stack changed. The following steps describe how pathlets are modified by $u$ and which messages are generated by $u$ to disseminate this information.

1) $u$ informs all its neighbors that its label stack has changed. To this purpose, $u$ sends to each of its neighbors a Hello message $M$ with $M.s = S_{new}$, $M.d$ set according to the network destinations available at $u$, and $M.a = \text{false}$.

2) $u$ considers the atomic pathlets towards its neighbors. Since the stack change may influence the scope stack of some of these pathlets, $u$ may have to update and disseminate them to a relevant subset of neighbors. Observe that, because of the propagation conditions and of the routing policies, an updated atomic pathlet may not be propagated to the same neighbors to which it was propagated before the stack change. Hence, $u$ will send to some neighbors Pathlet messages that announce or update some atomic pathlets, and to other neighbors Withdrawal messages that withdraw atomic pathlets that should no longer be visible. Formally, for each neighbor $v$ of $u$, if $(S_{old} \times S_u(v)) \neq (S_{new} \times S_u(v))$, $u$ searches $\Pi_u$ for an atomic pathlet $\pi_{old} = (\text{FID}, u, v, \sigma_{old}, \delta)$ from $u$ to $v$. Such pathlet must exist, because at least it has been created immediately after $u$ has received a Hello message from $v$. Let $\pi_{new} = (\text{FID}, u, v, \sigma_{new}, \delta)$, with $\sigma_{new} = (S_{new} \times S_u(v)) \circ (\bot)$. Then, $u$ executes procedure UpdateKnownPathletsAndStack($u$, $S_{old}$, $S_{new}$, $\Pi_u\setminus\{\pi_{old}\} \cup \{\pi_{new}\}$) from Algorithm 2.

3) $u$ considers the areas to which its neighbors belong and updates its role of border vertex: if $u$ is no longer a border vertex for some areas after the stack change, it must delete all crossing and final pathlets for these areas and withdraw them to relevant neighbors. Conversely, if after the stack change $u$ becomes a border vertex for
some areas, it must create crossing and final pathlets for these areas and disseminate them to the relevant neighbors, according to the propagation conditions and to the routing policies. For the areas for which \( u \) continues to be a border vertex, it must check whether the pathlets that make up its crossing and final pathlets are still available, or whether new compositions are possible, and disseminate the corresponding information.

To realize these operations, \( u \) executes procedure \text{UpdateComposedPathletsAndStack}(u, S_{\text{old}}, S_{\text{new}}, (\Pi_u \setminus \{\pi_{\text{old}}\}) \cup \{\pi_{\text{new}}\})\), which is invoked within \text{UpdateKnownPathletsAndStack}.

**Update of network destinations** – When an administrative configuration change modifies the set of network destinations available at a certain vertex \( u \), all vertices that store a pathlet with \( u \) as an end vertex must have this pathlet updated with the new available destinations. To achieve this, \( u \) performs only step 1) of the stack change: this is enough to propagate the updated information. In fact, as shown in the next subsection, when a vertex \( v \) receives a Hello or a Pathlet message that carries already known information but for the set of destinations, \( v \) updates the pathlets it stores locally and forwards the updated information to its neighbors, according to the propagation conditions and to the routing policies.

**E. Message Handling**

In the previous subsections we have described the actions performed by a vertex when it detects a topological change or it undergoes a configuration change. Therefore, to complete the specification of the control plane, we need to specify the behavior of a vertex when it receives any of the messages introduced in this section. Assume that vertex \( u \) receives a message \( M \). The actions performed by \( u \) depend on the type of message \( M \), and are detailed in the following.

**Receipt of a Hello Message** – When a vertex \( u \) receives a Hello message \( M \) from a neighbor \( M.o \), it performs several actions.

First of all, \( u \) updates its knowledge about vertex \( M.o \) by setting \( S_u(M.o) = M.s \) and \( D_u(M.o) = M.d \).

After that, \( u \) checks whether \( M.a = \text{True} \), which means that this is the first Hello message sent by \( M.o \) since its activation. If this is the case, vertex \( M.o \) needs to learn about all the currently available pathlets. For this reason, \( u \) sends to \( M.o \) all the information it currently knows, and in particular: for every pathlet \( \pi = \langle FID, v, w, \sigma, \delta \rangle \) in any of the sets \( \Pi_u, C_u, F_u \) kept by \( u \) such that \( M.o \in N(u, S(u), \sigma) \), \( u \) sends to \( M.o \) a Pathlet message \( M_p \) with \( M_{p,o} = v \), and \( M_{p,c} = t \), where \( t \) is taken from entry \( \langle FID, v, \sigma, t, + \rangle \) in history \( H_u \) (note that such an entry must exist for every pathlet learned or created by \( u \)). Moreover, for every entry \( \langle FID, v, \sigma, t, - \rangle \) in history \( H_u \) such that \( M.o \in N(u, S(u), \sigma) \), \( u \) sends to \( M.o \) a Withdrawlet message \( M_w \) with \( M_{w,f} = FID, M_{w,s} = \sigma, M_{w,o} = v, \) and \( M_{w,c} = t \). Observe that, in sending these messages, \( u \) preserves the origin vertex and timestamp of the originally learned information, as specified in the history.

At this point, \( u \) creates or updates pathlets as required, based on the newly learned information about its neighbor \( M.o \). As a first step, \( u \) creates an atomic pathlet towards \( M.o \), or updates it if it already exists in \( \Pi_u \). Since this action may change the contents of \( \Pi_u \), several crossing and final pathlets may also need to be created or deleted, based on the availability of their component pathlets. Moreover, after \( u \) has learned about the label stack of \( M.o \), it can detect that its status of border vertex for some areas has changed (it may become border vertex for some new areas and cease being border vertex for other areas), and this also requires updating crossing and final pathlets.

More formally, let \( \pi_{\text{new}} = \langle FID_{\text{new}}, u, v, \sigma_{\text{new}}, \delta_{\text{new}} \rangle \) be a new atomic pathlet from \( u \) to \( M.o \), with \( FID_{\text{new}} \) chosen to be unique at \( u \), \( v = M.o, \sigma_{\text{new}} = (S(u) \times S_u(v)) \circ (\perp) \), and \( \delta_{\text{new}} = D_u(v) \). If a pathlet \( \pi_{\text{old}} = \langle FID_{\text{old}}, u, v, \sigma_{\text{old}}, \delta_{\text{old}} \rangle \) exists in \( \Pi_u \), then let \( FID_{\text{new}} = FID_{\text{old}} \) (that is, the old pathlet is updated) and \( \Pi_{\text{old}} = \{\pi_{\text{old}}\} \); otherwise, let \( \Pi_{\text{old}} = \emptyset \). To realize all the required pathlet update operations, including those of crossing and final pathlets, and disseminate the updated information, \( u \) executes procedure \text{UpdateKnownPathlets}(u, (\Pi_u \setminus \Pi_{\text{old}}) \cup \{\pi_{\text{new}}\}) \) from Algorithm 2.

Note that, even if vertex \( M.o \) has sent an updated label stack, for example due to a stack change, it may be the case that no pathlets are updated by \( u \) and no messages are sent by \( u \). In fact, if the atomic pathlet \( \pi_{\text{old}} \) from \( u \) to \( M.o \) already existed in \( \Pi_u \) and its scope stack \( \sigma_{\text{old}} \) and set of destinations \( \delta_{\text{old}} \) are unchanged in \( \pi_{\text{new}} \) (which, for the scope stack, only requires that \( S(u) \times S_u(v) \) is unchanged), \( u \) does not perform any actions: this is visible in Algorithm 2 because the two for cycles at lines 2 and 13 execute no iterations since \( \Pi_{\text{new}} = \Pi_u \); moreover, if \( S(u) \times S_u(v) \) is unchanged, \( u \) cannot change either the areas for which it is a border vertex or any of the sets \( B_u \), and this causes sets \( C_{\text{old}} \) and \( C_{\text{new}} \) in Algorithm 4 to be empty, resulting in no actions being performed even during the execution of that algorithm.

Last, \( u \) checks whether the set of available destinations at its neighbor \( M.o \) has changed. In particular, for each pathlet \( \pi_{\text{old}} = \langle FID, u, v, \sigma, \delta \rangle \) in \( \Pi_u \) or in any of the sets \( F_u \) such that \( w = M.o \) and \( \delta_{\text{old}} \neq D_u(w) \), \( u \) sends to all its neighbors in \( N(u, S(u), \sigma) \) a Pathlet message \( M \) with \( M.p = \pi_{\text{new}} \), where \( \pi_{\text{new}} = \langle \langle FID, v, w, \sigma, D_u(w) \rangle \rangle \).

**Receipt of a Pathlet Message** – Upon receiving a Pathlet message carrying a pathlet \( \pi_{\text{msg}} = M.p \), a vertex \( u \) first of all checks the freshness of the information contained in that message: if the information contained in the message is older than the information that \( u \) currently has about \( \pi_{\text{msg}} \), \( u \) must send back a message with the updated information; otherwise, \( u \) accepts the fresher information and updates its pathlets and history accordingly.

In particular, let \( \pi_{\text{msg}} = \langle FID, v, w, \sigma_{\text{msg}}, \delta_{\text{msg}} \rangle \). If \( u \) is the originator of \( \pi_{\text{msg}} \), namely \( u = v \), then the information known by \( u \) about \( \pi_{\text{msg}} \) is to be considered always fresher, and the message can never carry updated information. If \( u \) is not the originator of \( \pi_{\text{msg}} \), the freshness of message \( M \) is determined by comparing the message timestamp \( M.c \) with
the timestamp of the most recent information that \( u \) keeps about \( \pi_{msg} \) in its history \( H_u \). In all the cases in which the information received in message \( M \) is outdated, \( u \) replies with a message containing the updated information. Function \( \text{ISPATHLETMESSAGEFRESHER}(u, M) \) in Algorithm 5 realizes this freshness check and returns \( \text{True} \) only when message \( M \) carries updated information. This function also sends updated information back to \( M_{src} \), forwards the received message to relevant neighbors, and updates the history \( H_u \) as required.

\( u \) therefore executes function \( \text{ISPATHLETMESSAGEFRESHER}(u, M) \); if it returns \( \text{False} \), the handling of \( M \) by \( u \) is finished, because the message does not carry any useful information (and function \( \text{ISPATHLETMESSAGEFRESHER} \) already takes care of forwarding the Pathlet message as appropriate). Otherwise, \( u \) looks in its set \( \Pi_u \) for a pathlet \( \pi_{old} = \langle FID, v, w, \sigma_{old}, \delta_{old} \rangle \). If this pathlet exists, \( u \) sets \( \Pi_{old} = \{ \pi_{old} \} \), otherwise \( u \) sets \( \Pi_{old} = \emptyset \). At this point, \( u \) updates its sets of known pathlets, crossing pathlets, and final pathlets, as well as its status of border vertex and sets \( B_u \) of other border vertices, and disseminates updated information to its neighbors. All these tasks are accomplished by \( u \) by executing procedure \( \text{UPDATEKNOWNPATHLETS}(u, (\Pi_u, \Pi_{old}) \cup \{ \pi_{msg} \}) \).

### Receipt of a Withdrawlet Message

Handling of a Withdrawlet message \( M \) received by a vertex \( u \) is much similar to that of a Pathlet message. First of all, \( u \) checks the freshness of the information carried by \( M \) by invoking function \( \text{ISWITHDRAWLETTMESSAGEFRESHER}(u, M) \) in Algorithm 6; if this function returns \( \text{False} \), then handling of message \( M \) is completed.

Otherwise, \( u \) searches \( \Pi_u \) for pathlet \( \pi_{old} = \langle FID, w, v, M_{src}, W, M_{dest}, \delta \rangle \). If this pathlet exists in \( \Pi_u \), \( u \) updates pathlets and disseminates information by executing procedure \( \text{UPDATEKNOWNPATHLETS}(u, (\Pi_u \setminus \{ \pi_{old} \}) \cup \{ \pi_{msg} \}) \); otherwise \( u \) undertakes no further actions, because there is no pathlet to be withdrawn. Note that, regardless of whether \( \pi_{old} \) exists in \( \Pi_u \), function \( \text{ISWITHDRAWLETTMESSAGEFRESHER} \) already takes care of appropriately forwarding the Withdrawlet message.

### Receipt of a Withdraw Message

Receiving a Withdraw message \( M \) has the same effect of receiving several Withdrawlet messages, all with the same timestamp \( t \), one for each \( FID \) of the pathlets in \( \Pi_u \) that have scope stack \( M_{scope} \) and start vertex \( M_{start} \). In order to handle this type of message, function \( \text{ISWITHDRAWLETTMESSAGEFRESHER} \) needs to be slightly modified as follows: if \( M \) carries fresher information for all the pathlets in \( \Pi_u \) with scope stack \( M_{scope} \) and start vertex \( M_{start} \), then history \( H_u \) is appropriately updated for all these pathlets and only the single Withdraw message is further propagated by \( u \); otherwise, if \( u \) has a more recent history entry in \( H_u \) for at least one of these pathlets, \( u \) treats the Withdraw message exactly as a sequence of Withdrawlet messages, sending back to \( M_{src} \) single Pathlet and Withdrawlet messages with updated information, and forwarding single Withdrawlet messages as appropriate.

If \( M \) is determined to carry fresh information, pathlets are then updated by \( u \) as already explained for the Withdrawlet message.

### VI. Applicability Considerations

In this section we describe how the control plane we have formally defined can be implemented in real-world, and we explain how further requirements, like support for Quality of Service levels, can easily be accommodated in our model. It is out of the scope of this paper to detail the configuration language that would have to be used to configure our control plane.

#### Technologies

The control plane we have defined in the previous sections is completely independent of the data plane that carries its messages: network destinations carried by Pathlet messages are completely generic and each vertex only communicates with its immediate neighbors, and to achieve this a simple link-layer connectivity is required. However, the information collected by our control plane can only be fully exploited if a data plane that can handle pathlets is available. As also explained in Section IV, data packets should have an additional header that specifies the sequence of FIDs of the pathlets that the packet is to be forwarded along. When a router receives a packet, it looks at the topmost FID, retrieves the next-hop router that corresponds to that FID, removes the FID from the packet’s header, and forwards the packet to the next-hop router. If the FID corresponds to a crossing or final pathlet, the router also alters the packet’s header by prepending the FIDs of the component pathlets before forwarding it. We highlight that the sequence of FIDs can be represented by a stack of labels and the operations we have described actually correspond to a label swap. For this reason, it is easy to implement the data plane of pathlet routing, as well as our control plane, on top of MPLS. The authors of [1] share the same vision in [15], yet they underline that MPLS does not allow to implement an overlay topology, which is very useful to specify, e.g., local transit policies. We argue that, unlike [1], our control plane is conceived for internal routing in an ISP’s network, a different scenario where MPLS is a commonly adopted technology and different requirements exist in terms of routing policies.

#### Incremental Deployment

It is of course unrealistic for an Internet Service Provider to change the internal routing protocol in the whole network in a single step. Our control plane is therefore designed to support an incremental deployment, so that a pathlet-enabled zone of the network that adopts our control plane and an MPLS data plane can nicely coexist with other non-pathlet-enabled zones of the same network that use different control and data planes. Assuming that non-pathlet-enabled zones use IP (possibly in combination with MPLS), we have two interesting situations: a pathlet-enabled zone is embedded in an IP-only network (initial deployment phase) or an IP-only zone is embedded in a pathlet-enabled network (legacy zones that may remain after the deployment). The first scenario can be easily implemented by making routers at the boundary of the two zones redistribute IP prefixes from the
Algorithm 5 Algorithm to determine whether a Pathlet message $M$ carries updated information about a pathlet: the function returns True only in this case. It also handles message forwarding and history update.

1: function IsPathletMessageFresher$(u, M)$
2:     $\pi_{\text{msg}} \leftarrow M.p$
3:     Let $\pi_{\text{msg}} = \langle \text{FID}, v, w, \sigma_{\text{msg}}, \delta_{\text{msg}} \rangle$
4:     if $u = v$ then
5:         $u$ is the originator of pathlet $\pi_{\text{msg}}$
6:     if there is no pathlet identified by $\text{FID}$ and with start vertex $u$ in $\Pi_u$ or in any of the sets $C_u$ and $F_u$ then
7:         $M_W \leftarrow$ new Withdrawlet message
8:         $M_W.f \leftarrow \text{FID}$
9:         $M_W.s \leftarrow \sigma_{\text{msg}}$
10:        Send $M_W$ to neighbor $M.src$
11:    else
12:        $\pi_{\text{cur}} \leftarrow$ pathlet identified by $\text{FID}$ and with start vertex $u$ that is known at $u$
13:        if $\pi_{\text{msg}} \neq \pi_{\text{cur}}$ then
14:            $M_P \leftarrow$ new Pathlet message
15:            $M_P.p \leftarrow \pi_{\text{cur}}$
16:            Send $M_P$ to neighbor $M.src$
17:        end if
18:    end if
19:    else
20:        return False
21:    end if
22: if $\exists \langle \text{FID}, v, \sigma, t, \text{type} \rangle$ in $H_u$ then
23:    if $t < M.t$ then
24:        Replace $\langle \text{FID}, v, \sigma_{\text{msg}}, t, \text{type} \rangle$ in $H_u$ with $\langle \text{FID}, v, \sigma_{\text{msg}}, M.t, + \rangle$
25:        for each $n \in N(u, S(u), \sigma_{\text{msg}}) \setminus \{M.src\}$ do
26:            Send $M$ to neighbor $n$
27:        end for
28:        return True
29:    else
30:        if $\text{type} = +$ then
31:            $\pi_{\text{cur}} \leftarrow$ pathlet in $\Pi_u$ identified by $\text{FID}$ and with start vertex $v$
32:            $M_P \leftarrow$ new Pathlet message
33:            $M_P.p \leftarrow \pi_{\text{cur}}$
34:            $M_P.t \leftarrow t$
35:            Send $M_P$ to neighbor $M.src$
36:        else
37:            $M_W \leftarrow$ new Withdrawlet message
38:            $M_W.f \leftarrow \text{FID}$
39:            $M_W.s \leftarrow \sigma$
40:            $M_W.t \leftarrow t$
41:            Send $M_W$ to neighbor $M.src$
42:        end if
43:        return False
44:    end if
45: else
46:        Add $\langle \text{FID}, v, \sigma_{\text{msg}}, M.t, + \rangle$ to $H_u$
47:        for each $n \in N(u, S(u), \sigma_{\text{msg}}) \setminus \{M.src\}$ do
48:            Send $M$ to neighbor $n$
49:        end for
50:        return True
51:    end if
52: end function
Algorithm 6 Algorithm to determine whether a Withdrawlet message \( M \) carries updated information about a pathlet: the function returns True only in this case. It also handles message forwarding and history update.

1: function IS_WITHDRAWLET_MESSAGE_FRESHER\((u, M)\)
2: if \( \exists (M.f,M.o,\sigma,t,\text{type}) \) in \( H_u \) then
3: if \( t < M.t \) then
4: Replace \( (M.f,M.o,\sigma,t,\text{type}) \) in \( H_u \) with \( (M.f,M.o,M.s,M.t,\text{--}) \)
5: for each \( n \in N(u,S(u),M.s)\setminus\{M.src\} \) do
6: Send \( M \) to neighbor \( n \)
7: end for
8: return True
9: else
10: if \( \text{type} = + \) then
11: \( \pi_{cur} \leftarrow \) pathlet in \( \Pi_u \) identified by \( M.f \) and with start vertex \( M.o \)
12: \( M_P \leftarrow \) new Pathlet message
13: \( M_P.f \leftarrow \pi_{cur} \)
14: \( M_P.t \leftarrow t \)
15: Send \( M_P \) to neighbor \( M.src \)
16: else
17: \( M_W \leftarrow \) new Withdrawlet message
18: \( M_W.f \leftarrow M.f \)
19: \( M_W.s \leftarrow M.s \)
20: \( M_W.t \leftarrow t \)
21: Send \( M_W \) to neighbor \( M.src \)
22: end if
23: return False
24: end if
25: else
26: There is no history entry for the pathlet withdrawn by \( M \), therefore \( u \) cannot know anything about that pathlet. However, the Withdrawlet must still be forwarded
27: Add \( (M.f,M.o,M.s,M.t,\text{--}) \) to \( H_u \)
28: for each \( n \in N(u,S(u),M.s)\setminus\{M.src\} \) do
29: Send \( M \) to neighbor \( n \)
30: end for
31: return False
32: end if
33: end function

IP control plane to the pathlet control plane: this means that boundary routers appear as the originators of these destination prefixes in the pathlet zone. Each boundary router then creates final pathlets to get to the destinations originated by the other boundary routers: the IP prefixes that boundary routers learn from the pathlet zone in this way are then redistributed from the pathlet control plane to the IP control plane. Likewise, the IP prefixes of destinations that are available at routers within the pathlet zone are also redistributed to the IP control plane. In this way, IP-only routers can reach destinations inside the pathlet zone or just traverse it as if it were a network link. As a small exception to what we have shown in Section III, in this scenario boundary routers need to compose final pathlets even if they just belong to area \( A_{(u)} \). From the point of view of the data plane, packets that enter the pathlet-enabled zone will have suitable FIDs pushed on their header, indicating the pathlets to be used to reach another boundary router or a destination within the pathlet zone; these FIDs will be removed when packets exit the pathlet-enabled zone. The second scenario can be implemented by assuming that routers at the boundary of the two zones have a way to exchange the pathlets they have learned by exploiting the IP-only control plane: for example, this could be achieved by tunneling Pathlet messages in IP or by transferring pathlet information suitably encoded in BGP messages (possibly in the AS path attribute). Boundary routers then redistribute from the pathlet control plane to the IP control plane the IP prefixes they have learned from the final pathlets: in this way, the boundary routers appear as the originators of these prefixes in the IP-only zone. Moreover, each boundary router will disseminate final and crossing pathlets that lead, respectively, to destinations inside the IP-only zone or to other boundary routers. In this way, the IP-only zone can be traversed (or its internal destinations be reached) without revealing its internal routing mechanism, and appears just as if it were an area of the pathlet zone. From the point of view of the data plane, a packet containing FIDs in its header must be enabled to traverse the IP-only zone: this can be easily achieved by establishing tunnels between pairs of boundary routers. Of course there is no sharp frontier between the first and the second scenario, because the roles of “embedded” and “embedder” zone can be easily swapped: although they best fit specific phases of the deployment, both choices can indeed be permanently adopted, and it is up to the administrator to decide which one is it best to apply.

Quality of Service – We have designed our control plane to
support the computation of multiple paths between the same pair of routers. Besides improving robustness, this feature can also be exploited to support Quality of Service. In particular, each pathlet could be labeled with performance indicators (delay, packet loss, jitter, etc.) that characterize the quality of the path that it exploits. Upon creating a crossing or final pathlet, a router will update the performance indicators according to those of the component pathlets. When multiple pathlets are available between the same pair of routers, a router will be able to choose the one that best fits the QoS requirements for a specific traffic flow.

**Software Defined Networking** – A relatively recent trend in computer networks is represented by the separation of the logic of operation of the control plane of a device from the (hardware or software) components that take care of actual traffic forwarding. This trend, known as Software Defined Networking, has a concrete realization in the OpenFlow protocol specification [16]. We believe that our approach has several elements that make it compatible with an OpenFlow scenario. First of all, the fact that packets are forwarded according to the sequence of FIDs contained in their header is a form of source routing: this matches with the OpenFlow mechanism of setting up flow table entries to route all the packets of a flow along an established path. Moreover, a recent contribution [17] proposes a hierarchical architecture for an OpenFlow network: the authors suggest that a set of devices under the coordination of a single controller can be seen as a single logical device that is part of a larger OpenFlow network, in turn having its own controller. Following this approach, we could assign an OpenFlow controller instance to each area defined in our control plane, and these instances could be organized in a hierarchy that simply reflects the hierarchy of areas: in this way, each instance can direct traffic along the desired sequence of pathlets within the area that it controls, whereas instances at higher levels of the hierarchy can only see lower controllers as a single entity, reflecting the idea of crossing pathlet.

**VII. Experimental Evaluation**

In order to verify the effectiveness of our approach and to assess its scalability, we have performed several experiments in a simulated scenario. For this purpose we used OMNeT++ [18], a component-based C++ simulation framework based on a discrete event model. We considered a few other alternative platforms, including, e.g., the Click modular router [19], but in the end we selected OMNeT++ because it has a very accurate model of a router’s components, like Click, and it also allows to run on a single machine a complete simulated network with realistic parameters, such as link delay. Moreover, there exist lots of ready-to-use extensions for OMNeT++ that allow the simulation of specific scenarios, including IP-based networks. To consider a realistic setup, we therefore chose to build a prototype implementation of our control plane based on the IP implementation made available in the INET framework [20], a companion project of OMNeT++. In our prototype, the messages of our control plane are exchanged encapsulated in IP packets with a dedicated protocol number in the IP header. We implemented most of the mechanisms described in Sections IV and V, with very few exceptions that are not relevant for the purposes of our experiments. In particular, we implemented all the message types (except fields carrying network destinations), all the propagation conditions, the mechanisms to discover border vertices for an area and to compose atomic and crossing pathlets, the history at each vertex, and a relevant portion of the forwarding state (the mapping between a pathlet and its component pathlets). Some of the algorithms adopted in our implementation may still not be tuned for best efficiency, but this is completely irrelevant because we measured routing convergence times by using the built-in OMNeT++ timer, which reflects the event timings of the simulation, instead of the wall clock.

Each simulation we ran had two inputs: a topology specification, consisting of routers, links, assignment of label stacks to routers, and link delays; and an IP routing specification, consisting of assignments of IP addresses to routers’ interfaces and of insertion of static routes for the networks that were directly connected to each router. In order to facilitate the automated generation of large topologies, we assigned to each link a /30 subnet selected according to a deterministic but completely arbitrary pattern.

We first executed several experiments in a small topology with a well-defined structure encompassing border routers for several areas. This topology consisted of 15 routers, 20 edges, 4 areas with a maximum length of the label stacks equal to 3 (including label \(l_h\)), and at least 3 vertices in each area. This helped us to thoroughly verify the implementation for consistency. We then implemented a topology generator and used it to create larger topologies that could allow us to assess the scalability of our control plane. The topology generator works by creating a hierarchy of areas and by adding routers and links randomly to the areas. It takes the following parameters as input: length \(N\) of the label stack of all the routers; number of routers having a stack of length \(N\), specified as a range \([R_{\text{min}},R_{\text{max}}]\), with possibly \(R_{\text{min}} = R_{\text{max}}\); number of areas contained in each area, specified as a range \([A_{\text{min}},A_{\text{max}}]\), with possibly \(A_{\text{min}} = A_{\text{max}}\); probability \(P\) of adding an edge between two vertices; fraction \(B\) of the routers within an area that act as border routers for that area (namely that can have links to vertices outside that area). The topology generator proceeds by recursively creating areas, starting from a single area that comprises all vertices. The complete procedure is described in Algorithm 7.

A detailed description of the experiments we carried on follows. This description is still in a drafty form and will be improved in a future release of this technical report.

Two preliminary experiments were carried out to assess the scalability of our control plane. In both experiments, we ran several simulations where the size of the topology were increased. To increase the size of the topology we adopted the following strategy. Every input parameter of the topology generator was fixed, except one that has been used to change the size of the topology. In the first experiment, the number
of areas contained in each area was chosen as the variable input, while in the second experiment, the length of the label stack was chosen as the variable input. For each simulation, we collected data regarding the number of messages sent by each router, the number of pathlets stored in each router, and the convergence time of the protocol. Because of difficulty with the OMNeT framework, our simulation were performed with topologies with a limited level of multipath. As a consequence, we ran simulations on topologies whose bottom-level areas exposes a limited level of multipath. On average, there are 3 – 4 different paths between two border vertices of a bottom-level area.

**Statistical tools** - The analysis of the collected data involves the knowledge of several widely adopted statistical tool. We introduce them and we try to give intuitions of their meaning. We use linear regression analysis to determine the level of correlation (linear dependence) between two arbitrary variables \( X \) and \( Y \). A linear regression analysis returns a line \( l_Y(X) = A + BX \) that is an estimate of the value \( Y \) with respect to \( X \). The estimation of \( l_Y \) depends on the specific measure of accuracy that is adopted. In our analysis, we use the Ordinary-Least-Square (OLS) method for estimating coefficients \( A \) and \( B \) of \( l_Y \). Observe that \( B \) is extremely relevant in the analysis of the result since it can be interpreted as an estimation of the increase of \( Y \) for each additioanl unit of \( X \). To verify if there exists a linear relation between \( X \) and \( Y \), we look at the coefficient of determination \( R^2 \). An \( R^2 \) close to 1.0 indicates that the relation between \( X \) and \( Y \) is roughly linear, while an \( R^2 \) closer indicates that the relation does not seem to be linear. To determine the level of dispersion of the observed values for \( X \) and \( Y \) with respect to \( l_Y \), we look at the standard error of the regression (SER) of \( l_Y \). This value has the same unit of values in \( Y \) and can be interpreted as follows: approximately 95% of the points lie within \( 2 \times SER \) of the regression line. Sometimes, it is better to look at a normalized value that represents the level of dispersion of a set of values \( X \). This can be done, by computing the coefficient of variation \( c_v \) of \( X \) which is independent of the unit in which the measurement has been taken and can be interpreted as follows: given a set of values \( X \), approximately 68% of the values lie between \( \mu(1 – c_v) \) and \( \mu(1 + c_v) \), approximately 95% of the values lie between \( \mu(1 – 2c_v) \) and \( \mu(1 + 2c_v) \), and approximately 99.7% of the values lie between \( \mu(1 – 3c_v) \) and \( \mu(1 + 3c_v) \), where \( \mu \) is the arithmetic mean of \( X \).

**Experiment 1** - We constructed network topologies using the following fixed parameters: \( R_{\min} = R_{\max} = 10 \), \( N = 2 \), \( P = 0.1 \) and \( B = 5 \). The variable input \( A_{\min} = A_{\max} \) varied from 2 to 7. Roughly speaking, we keep a constant number of levels in the area hierarchy while increasing the number of areas in the same level. For each combination of these values, we generated 10 different topologies and for each of these topologies, we ran an OMNeT++ simulation and collected relevant data as previously specified. In Fig. 5 (Fig.4) we show that the maximum (average) number of pathlets stored in each router (depicted as crosses) grows with respect to the number of edges in the topology. In particular, the growth is approximately linear as confirmed by a linear regression analysis (depicted as a line) performed on the collected data. The slope of the line is 0.83 (0.75), which can be interpreted as follows: for each new edge in the network, we expect that the value of the maximum (average) number of pathlets stored in each router increases by a factor of 0.83 (0.75) on average. To assess the linear dependence of the relation, we verified that the \( R^2 = 0.87 \) (\( R^2 = 0.9 \)), which means that the linear regression is a good-fit of the points. The standard error of the regression is 39.8 (9.26), which can be interpreted as follows: approximately 95% of the points lie within \( 2 \times 39.8 \) (\( 2 \times 9.26 \)) of the regression line. We motivate the linear growth as follows. Observe that, each topology has a fixed number \( A_{\max} \) of areas and therefore the expected number of crossing pathlets created for any arbitrary area is the same. Hence, by increasing \( A_{\max} \), since the number of crossing pathlet created in each area grows linearly with \( A_{\max} \), we have that also the number of pathlets stored in each router, which contains a constant number of atomic pathlets plus each crossing pathlet created by border router of neighbors areas, grows linearly. In Fig. 3 (Fig.2) we show that similar results hold also when we analyze the average/maximum number of messages by each router. In fact, we observed that many considerations that we made with respect to the number of messages sent by each router, are also valid with respect to the number of pathlets stored in each router. In fact, as shown in Fig. 7, we show that there exists an interesting linear dependence, with \( R^2 = 0.87 \), between the number of messages sent by each router and the number of pathlets stored in each router.

**Experiment 2** - We constructed network topologies using the following fixed values: \( R_{\min} = R_{\max} = 10 \), \( A_{\min} = A_{\max} = 2 \), \( P = 0.1 \) and \( B = 5 \). The variable input \( N \) varied in the range between 1 and 4. Roughly speaking, we keep a constant number of subareas inside an area, while we increase the level of area hierarchy. For each combination of these values, we generated 10 different topologies and for each of these topologies, we run an OMNeT++ simulation and the same data as in the first experiment. In Fig. 11 (Fig.10) we see that the maximum (average) number of pathlets stored in each router (depicted as crosses) grows linearly with respect to the number of edges in the topology. A linear regression analysis computed over the collected data shows that the slope of the line is 1.38 (0.94), which can be interpreted as follows: for each new edge in the network, we expect that the value of the maximum (average) number of pathlets stored in each router increases by a factor of 1.38 (0.94) on average. To assess the linear dependence of the relation, we verified that the \( R^2 = 0.75 \) (\( R^2 = 0.81 \)), which can still be considered a good-fit of the points. As for the dispersion of the points with respect to the line, it is easy to observe that, the higher the number of edge, the higher the dispersion. If we look to the standard error of the regression, since the measure is not normalized, we may obtain an inaccurate value of the dispersion. Therefore, we do the following. We consider 4 partition \( P_1, \ldots, P_4 \) of the measurements, where \( X_i \) contains each measure collected when \( N = i \), and compute the coefficient of variation \( c_v \) of each
subset. We observe that $c_i$ varies between 0.21 and 0.42 (0.24 and 0.31), which means that in each partition $X_i$, 95% of the points lie within $2 \cdot 0.41\mu$ (2 · 0.31$\mu$) of the mean $\mu$ of $X_i$. We have not enough data to check whether there exists a linear dependence between the value $c_i$ of a partition $X_i$ and the index $i$.

We motivate the linear growth as follows. Observe that each bottom area construct on average the same number of crossing pathlets, regardless the levels of the hierarchy. Because of the low values chosen for $P$, $A_{\text{min}}$, and $A_{\text{max}}$, the number of crossing pathlets created by higher areas is roughly proportional to the number of crossing pathlets created by its subareas. Now, consider the set of pathlets stored in a router with stack label $(x_1 \ldots x_n)$. It contains atomic pathlets for the areas in which it belongs, which are logarithmic with the number of edges, and it contains crossing pathlets from other areas, which are roughly proportional to the number of bottom-level areas. Hence, each time $N$ is increased, both the number of edges and the number of bottom-level areas, grows exponentially with the same rate, and therefore the number of pathlets stored in each router increases linearly with respect to the number of edges. As for the first experiment, a similar trend can be seen also in Fig. 9 and Fig. 8 with respected to the maximum and average number of messages sent by a router, respectively. In fact, also in this experiment, we observe that there is a good linear relation between the number of messages sent by a vertex and the number of pathlets stored in each router (see Fig. 13).

Convergence time - We now consider the convergence time $T$ of the protocol expressed in milliseconds. In both experiments we set link delays as random uniform variable in the range between 10 and 50 milliseconds. Convergence time for the first and the second experiments with respect to the size of the network (expressed by the number of edges) are shown in Fig. 6 and 12, respectively. In Experiment 1 we achieved $T \in [363, 611]$ whereas in Experiment 2 $T \in [259, 736]$. The minimum value in both the intervals correspond to the minimum value among the 10 different generated topologies with the value $A = 2$ and the value $L = 1$ respectively for Experiment 1 and Experiment 2; on the other hand the maximum value in both the intervals is the maximum value among the 10 different generated topologies with the value $L = 7$ and the value $L = 4$ respectively for Experiment 1 and Experiment 2.

In the first experiment, the value $T = 363$ msec was achieved for a topology with two areas, $A_{(0 \ 1)}$ and $A_{(0 \ 2)}$, both contained into area $A_0$, with $R_{\text{min}} = R_{\text{max}} = 10$ vertices per area. By random adding edges, we obtained a network with 20 vertices and 22 edges. On the other hand, the value $T = 611$ msec was achieved for a topology with $R_{\text{min}} = R_{\text{max}} = 10$ vertices per bottom-level area and $A_{\text{min}} = A_{\text{max}} = 7$ bottom-level areas contained into area $A_0$. By random adding edges, we obtained a topology with 70 vertices and 89 edges. As for the experiments that involve the length $N$ of the label stack, we obtained the value $T = 0.259$ msec for a network topology where all vertices belong only to the same area $A_0$. The generated network has 10 vertices and 12 edges. On the other hand, the value $T = 736$ msec was achieved for a network topology with $R_{\text{min}} = R_{\text{max}} = 10$ vertices per bottom-level area and the length of the label stack is $N = 4$. The generated topology has 80 vertices and 104 edges, with vertices organized into a network that have 2 areas at each level. In particular, $A_0$ contains two areas, $A_{(0 \ 1)}$ and $A_{(0 \ 2)}$. Each of these areas contains, in turn, two areas: $A_{(0 \ 1 \ 2)}$ and $A_{(0 \ 1 \ 3)}$ are contained into $A_{(0 \ 1)}$, while $A_{(0 \ 2 \ 3)}$ and $A_{(0 \ 2 \ 4)}$ are contained into $A_{(0 \ 2)}$ and so on.

In both experiments, we achieved a convergence time below 1 sec and we observed that the correlation between the size of the network and the convergence time, does not exhibit a linear behaviour. In Fig. 6 it can clearly be observed that the regression line does not fit well the points. The slope of the regression line is 1.2, which can be interpreted as follow: for each new edge in the network, we expect that convergence time increases of 1.2 milliseconds. However, we computed an $R^2$ value of 0.26, which is close to 0 and suggest a lack of correlation between convergence time and number of edges. In other word, the convergence time is independent from the number of edges. On the other hand, In Fig. 12 a more strong correlation between convergence time and number of edges seems to hold. In this case, the slope is 2.9 with an $R^2$ value of 0.57. This means that the growth appears to be linear but there is a high dispersion of the points from the line. We recall that both experiments has been run with a pathlet composition rule that force each border vertex to compose all the possible pathlets to every other border vertex of the same area. Changing this rule, we expect that convergence times will decrease.

Our prototype implementation, including the topology generator, is publicly available at [21].

VIII. CONCLUSIONS AND FUTURE WORK

In this paper we introduce a control plane for internal routing inside an ISP’s network that has several desirable
Algorithm 7 Algorithm used in our topology generator.

```plaintext
function POPULATEAREA(A, level, Rmin, Rmax, N, Amin, Amax, P, B)
    if level = N then
        r ← a random number in [Rmin, Rmax]
        Add r vertices to A
    repeat
        for each pair (u, v) of vertices in A do
            Add an edge between u and v with probability P
        end for
    until A is connected
    Randomly pick r × B routers in A and mark them as border routers for A
    else
        a ← a random number in [Amin, Amax]
        Create a areas inside A; let A be the set of these areas
        ¯R ← Ø
        for each ¯A in A do
            POPULATEAREA(¯A, level + 1, Rmin, Rmax, N, Amin, Amax, P, B)
        end for
    end if
    repeat
        E ← Ø
        for each pair (u, v) of routers in ¯R do
            Flip a coin with probability P
            if heads then
                Add an edge between u and v
                E ← E ∪ (u, v)
            end if
        end for
    until the undirected graph formed by vertices in ¯R and edges in E is connected
    Randomly pick | ¯R | × B routers in ¯R and mark them as border routers for A
    return A
end function

function TOPOLOGYGENERATOR(Rmin, Rmax, N, Amin, Amax, P, B)
    Create an area A
    level ← 1
    return POPULATEAREA(A, level, Rmin, Rmax, N, Amin, Amax, P, B)
end function
```

properties, ranging from fine-grained control of routing paths to scalability, robustness, and QoS support. Besides introducing the basic routing mechanisms, which are based on a well-known contribution [1], we provide a thorough and formally sound description of the messages and algorithms that are required to design such a control plane. We validate our approach through extensive experimentation in the OmNeT++ simulator, which reveals very promising scalability and convergence times. Our prototype implementation is available at [21].

There are a lot of improvements that we are still interested in working on. Some of them are possible optimizations, whereas others are foundational issues that are still open: here we mention a few. Our current choice of messages types imposes a strong coupling between routing paths and network destinations: if a network destination changes its visibility (for example, a router starts announcing a new IP prefix), several pathlets to that destination must be (re)announced, even though the routing has not changed. Inspired by recent research trends [22], we could change the protocol a bit to separate these two pieces of information. In line with this decoupling requirement, we would like to investigate on how to deal with dynamic changes in QoS levels associated with pathlets. Routing policies, especially pathlet composition rules, could of course be refined to accommodate further requirements that we have not considered yet. Moreover, their specification and application could be enhanced to improve scalability in common usage scenarios (for example, when several areas are grouped into a larger one). The pathlet expiration mechanism needs further improvements to correctly purge pathlets in the presence of routing policies. The handling of stack change
Fig. 3. Maximum number of messages sent by a router with respect to the number of edges contained in the topology. (Experiment 1)

Fig. 6. Network convergence time with respect to the number of edges contained in the topology. (Experiment 1)

Fig. 4. Average number of pathlets stored in a router with respect to the number of edges contained in the topology. (Experiment 1)

Fig. 7. Maximum number of pathlets stored in a router with respect to the maximum number of messages sent by a single router. (Experiment 1)

Fig. 5. Maximum number of pathlets stored in a router with respect to the number of edges contained in the topology. (Experiment 1)

Fig. 8. Average number of messages sent by a router with respect to the number of edges contained in the topology. (Experiment 2)
events could also be improved: in particular, we could design more effective mechanisms to transparently replace a pathlet that is no longer visible with other newly appeared pathlets, without spreading messages to the whole network. Being modeled as stack change events, the handling of faults could be improved likewise.

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