BANANAS: A Connectionless Framework for Explicit, Multipath Routing in the Internet*

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Abstract

This paper presents BANANAS, a connectionless framework for enabling explicit, multipath routing in the Internet. BANANAS uses the idea of a globally known path identifier, known as $PathID$ to achieve source [1] specified, explicit, multipath routing in a partially upgraded network. We show that BANANAS allows introduction of sophisticated explicit and multipath routing capabilities in the context of connectionless routing protocols (e.g. OSPF, IS-IS, BGP etc.). BANANAS provides various alternatives for managing space, speed and computational complexity. The BANANAS framework has been implemented in SSFNet simulator and Linux kernel using Click Router for the forwarding plane and Zebra for the control plane. Results from complexity analysis, SSFNet simulations and Linux/Zebra implementation at Utah's Emulab testbed have been used to evaluate and illustrate the BANANAS framework.

I. INTRODUCTION

Today's Internet routing protocols like OSPF and BGP were designed to provide one primary end-to-end service, "best effort reachability." These protocols realize the "best-effort" concept by offering a single-path to destination. However, the Internet topology has an intrinsic multiplicity of paths. Hosts have multiple potential network interfaces and both enterprise and ISP Autonomous Systems (ASes) are multi-homed [1], [2], [3].

It is interesting to ponder on two questions:

a) Why is path multiplicity a valuable architectural feature?

b) Why has the intrinsic path multiplicity in the Internet not been exploited?

The answer to the first question is that multi-path transmission can be fundamentally more efficient than the current single-path paradigm. Just like packet switching is fundamentally more efficient than circuit switching because it offers the potential to leverage both spatial and temporal multiplexing gains at a single link (see [4], Chapter 1, 2), a network offers one more dimension where spatio-temporal multiplexing gains may be obtained, different paths. Packet switching does not waste unused capacity if user demand is available at a single link; similarly, with path multiplicity available to end-to-end flows, unused capacity in paths will not be wasted if user demand is available. Using the proposed BANANAS framework, such multiple paths may be leveraged at different levels in the networking stack - legacy OSPF or BGP networks, overlay networks, peer-to-peer networks (e.g. dynamically instantiated overlays using a peer-to-peer lookup infrastructure to support video-conferencing) and last-mile multi-hop fixed-wireless networks.

The answer to the second question is clearly *not* the lack of algorithms and protocols. There have been several proposals for multipath route-computation [5], [6], [7], [8], Internet signaling architectures [9], [10], [11], [12], [13], novel overlay routing methods [14], [15] and transport-level approaches for multi-homed hosts [16], [17]. The fact that these developments have not triggered widespread deployment suggests that the core problem is an architectural one. We believe that the Internet lacks an evolutionary framework that admits incremental deployment of path multiplicity, while providing sufficient flexibility in terms of architectural function-placement and complexity management. This paper proposes to fill that void with a framework called "BANANAS". Recent work [18] has

[1] source refers to the first BANANAS upgraded router in the data path and not necessarily the source host

showed that with minor modifications, current Internet architecture may be evolvable. It is interesting to note that BANANAS architecture meets some of the basic requirements discussed in [18] such as evolutionary deployment, compatible with existing Internet protocols (OSPF, BGP etc.), not requiring prohibitive states at upgraded routers and providing flexible configuration and deployment options.

At the highest level, BANANAS proposes a simple extension of Internet operation to admit and leverage end-to-end path-multiplicity (PM). In this model, source-hosts initiate one or more end-to-end "flows" and map flows to local network interfaces. The "network" provides one or more end-to-end paths through the independent upgrades of a *subset* of network nodes, possibly situated in multiple administrative domains. A subset of these upgraded nodes (e.g. selected edge-nodes) may also map "flows" to available "paths" [2]. Observe that today's single-path model is a special case of this PM-model. The PM model also allows a subset of source-hosts and routers to be independently upgraded within the scope of usual administrative boundaries. Upgraded node may "see" only a subset of available paths within appropriate administrative boundaries. This high-level model is a *best-effort path multiplicity* model, clearly different from IPv4/IPv6 connectionless loose-source-routing model [19], [20] and from end-to-end signaled source-route models used in ATM networks (e.g. PNNI [21]) or MPLS networks [22].

BANANAS provides a set of concepts and building blocks to realize this high-level PM model. A core abstract idea in BANANAS is that a path can be efficiently encoded as a short hash (called the "PathID") of a sequence of globally-known identifiers (e.g. router IDs, link interface IDs, AS numbers etc.). This concept has some very important advantages. First, a hash-based data-plane encoding is more efficient than IPv4/IPv6's loose-source-routing encoding [19], [20] that is an uncompressed string of IP addresses. Second, since the PathID is a function of globally-known quantities, it inherits their global significance, i.e., it can be computed and interpreted within the same scope of visibility. This "global" scope may refer to a single routing domain if router/link IDs are involved; or may refer to the universe of BGP-4 routers if AS numbers are used. The global PathID semantics allow any upgraded multipath capable (MPC) router to autonomously compute the PathID without any changes to legacy single-path capable nodes. It also removes the need for an explicit out-of-band signaling protocol as a path-setup mechanism. Note that one purpose of signaling in ATM and MPLS is to map global identifiers (IP addresses, path specifications) to *locally* assigned identifiers i.e. labels. The global PathID semantics allow the mapping of BANANAS in an em incremental manner to *connectionless* Internet routing protocols (e.g. OSPF, BGP-4).

BANANAS can also be used for connectionless traffic engineering in the ISPs or enterprise networks. Traffic Engineering (TE) deals with the task of mapping traffic flows to the paths in an existing physical topology to meet the network and user performance objectives. BANANAS provides several advantages over existing TE approaches including providing network operators more control over the traffic routing, no excess control traffic overhead on changes in traffic demands, compatibility with existing protocols e.g. OSPF, BGP, incremental deployment and flexibility in managing overheads. We discuss these in more detail in the following paragraphs.

A desirable traffic engineering solution must provide network operators a precise control over the traffic flows

[2] E.g. Packets from TCP connections would be mapped single "path" to avoid out-of-order packets

within their routing domains. This enables them to provide new services by appropriately managing the traffic. BANANAS provides explicit routing control to network operators.

A common *connectionless* intra-domain TE uses a *parametric approach* where the routing algorithm only provides a single shortest path between any node pair, but the link weights are optimized to achieve TE objectives. If multiple equal cost paths are found, Equal Cost Multi Path (ECMP) splits traffic equally among next-hops of multiple equal cost paths. In the parametric approach the problem of mapping traffic to paths is $coupled$ with the problem of route calculation. The parametric approach will hence lead to a route change for any desired change in traffic mapping (or a change in the traffic demand matrix). This would lead to control traffic overhead (LSA re-advertisement) and computational overhead (recomputation of shortest paths) for every change in link weight. BANANAS allows decoupling of traffic splitting from route calculation. Therefore, a change in traffic demand matrix does not lead to extra computational or control overhead in BANANAS.

In contrast, Multi Protocol Label Switching (MPLS) is an example of a *connection-oriented* or *signaled* TE approach. MPLS allows explicit setup of label switched paths (LSPs), and arbitrary flexibility in mapping traffic to the available LSPs. Unlike parametric approach, MPLS decouples the traffic mapping problem from route calculation. However, due to the requirement of signaling, a fully-upgraded network is required. BANANAS also decouples the traffic mapping and route calculation while using a connectionless approach. This allows BANANAS to be easily mapped to legacy routing protocols such as OSPF, BGP. Moreover, BANANAS can be incrementally deployed in the Internet.

In addition to the above, BANANAS allows considerable flexibility in terms of architectural function placement and complexity management. These aspects of BANANAS are crucial for tailoring the proposed building blocks and establishing the appropriate incentives for adoption by vendors and ISPs. For example, the BANANAS allows considerable flexibility in the choice of multipath route-computation algorithms and the choice of hash functions for encoding PathID. An efficient index based scheme has been designed allowing fast, collision-free forwarding, low space and computation overhead in core routers while moving complexity to network edge routers. The tradeoff is a higher, possibly variable length per-packet overhead. The proposed BANANAS realizations have been evaluated using integrated OSPF/BGP simulations and Linux/Zebra implementations on Utah's Emulab testbed.

Note that the focus of this paper is to present the BANANAS architectural framework for enabling explicit, multipath routing in the Internet. This paper does not address the problems related to performance improvements, advantages and applications of PM model. Moreover, traffic mapping/splitting problem is not a focus of this paper.

The rest of the paper is organized as follows. Section II presents the BANANAS framework including the $PathID$ concept, packet forwarding, route computation and analysis of overheads for both canonical BANANAS configuration and the index-based scheme in a partially upgraded network. Section III summarizes the intra-domain routing extensions for link-state protocols, OSPF and IS-IS. Section IV develops the inter-domain ideas of BANANAS in the context of BGP-4. Section V presents both simulation and Linux-based implementation results to illustrate the architectural features of BANANAS. Section VI surveys the related work while comparing and contrasting it with BANANAS. Finally, summary and concluding remarks are presented in Section VII.

II. THE *BANANAS* FRAMEWORK

This section presents various components of the BANANAS framework. Section II-A introduces the concept and definition of "globally" known path identifier or $PathID$. Section II-B describes the packet forwarding whereas Section II-C discusses path computation in BANANAS under partial upgrade assumption. Section II-D discusses various overheads and tradeoffs associated with BANANAS.

A. Path Identifier: PathID

Consider a network modeled as a graph $G = (\mathcal{N}, E)$ where $\mathcal{N}$ is the set of vertices or nodes and E is the set of edges or links in the network. Let N denote the number of nodes in the network, i.e. the cardinality of the set $\mathcal{N}$. For each link $(i, j) \in E$, let $l_{i,j}$ denote a globally known identifier for the link. Let n_i denote a globally known identifier for node $i \in \mathcal{N}$. Consider a path $P_{i,j}$ from node i to node j, which passes through nodes $i, 1, 2, ..., m-1, j$. This path can be represented as a sequence of globally-known node and link identifiers $[n_i, l_{i,1}, n_1, l_{1,2}, n_2, ..., l_{m-1,j}, n_j]$. The path sequence can be compactly represented by a *hash* of its elements. A path identifier (or, "PathID" in short) is defined as a hash of the *above sequence or any non-null subsequence* derived from it. Figure 1 illustrates the concept of node identifier, link identifier and "PathID".

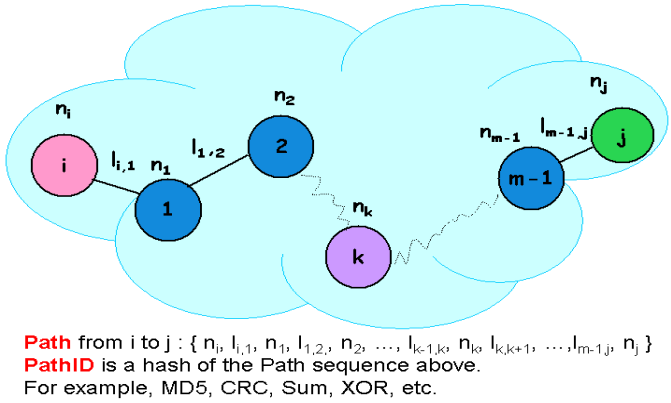


Fig. 1. Path and PathID Concepts

A desirable hash is compact, fast to compute and has a low collision probability (i.e. high uniqueness probability). A hash collision occurs when two distinct inputs into a hash function produce identical outputs. There is a tradeoff in using a long, complex, low-collision probability hash e.g. MD5 and an easy to compute, simple high collision probability hash e.g. XOR.

A sequence of globally known link interface IDs, router IDs (in OSPF or IS-IS) or AS numbers (in BGP) along the path can be used to generate the underlying *path sequence*. Link weights are globally known link attributes in OSPF/IS-IS networks but is not recommended as link identifiers in computing PathIDs. The path sequence generated by using link weights as link identifers may be non-unique itself. Moreover, if an ISP uses dynamic link weights to implement traffic engineering or adaptive routing, the PathIDs will change frequently. On the other hand

router IDs and link interface IDs are unique identifiers. Locally meaningful link IDs computed using a globally known scheme can also be used to compute a globally known PathID. Other interesting hash schemes such as reversible hash or bloom filters can be used for PathID computation. These lead to different realizations of the BANANAS framework.

In the canonical form, PathID can be a hash function such as MD5 or CRC designed to avoid PathID collisions. With canonical hash function used to compute PathID, a table lookup and exact PathID match is required at the intermediate routers to find the next hop information. If a reversible hash used to compute PathID, intermediate routers can derive the next-hop information from the PathID field in the packet header. This will reduce the computational and space complexity at core routers. This was the motivation in designing the index-based PathID encoding scheme described in Section II-A.2.

Hash schemes can also be designed using Bloom Filter [46] to efficiently encode the PathID. In this case, a set membership query can be used to find the next-hop information at intermediate routers. While the bloom filter may lead to false positives, a scheme can be designed to minimize the collision probability using bloom filters. Moreover, the collision occurs only when the next hop router is also a next-hop neighbor of the associated node.

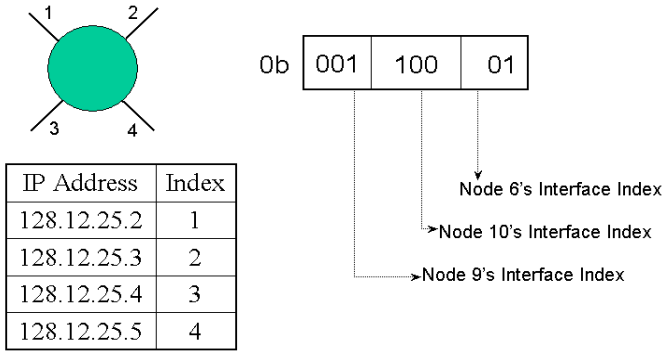
1) Canonical Scheme:PathID encoding: The canonical hash function choice in BANANAS is a 128-bit MD5 hash followed by a 32-bit CRC of the 128 bit MD5 hash (resulting in a final 32-bit hash value). We use the notation (MD5 + CRC32) hash to represent the above two-step hashing process. Alternatively, 32-bits of the 128-bit MD5 hash could also have been used. This hash value is used in conjunction with the destination address (j); leading to a two-tuple hash [j, PathID]. Since the hash value is used in conjunction with the destination address, the probability of collision is reduced substantially. In particular, hash collision will be effective only if PathIDs to same destination collide.

Assuming a 32-bit MD5+CRC32 is used as the hash function. For the ease of analysis we assume a random bit-string as input and all the 2^{32} outputs to be equally likely. Let k denote the number of paths to a given destination j. The k random input sequences are distinct, collision occurs if k draws out of 2^{32} leads to a collision. The probability of collision is $1 - \frac{(2^{32})!}{2^{32k}\,(2^{32}-k)!}$. Note that in practical situation, a router may keep, say, 5-10 paths to any given destination. Evaluating the above expression for $k = 10$ gives a collision probability of 1.0477^{-8}. The BANANAS forwards a packet on the default shortest path if the PathID match leads to more than one exact match. Note that using the PathID in conjunction with the destination IP address substantially reduces the collision probability.

2) Index-based Scheme: PathID Encoding: The goal is to design a scheme that derives the next-hop information from the PathID field itself and does not need a forwarding table lookup to forward the packet. In this scheme core routers need not compute multiple paths and store them into their forwarding tables.

The idea is to generate globally known link identifiers that can be computed locally. An upgraded node orders its link interface IDs (or alternatively neighbor node IDs)and represents each link by its index in this ordering (see Figure 2). This link ID, i.e. index, can now be efficiently encoded. For example, a router with 15 interfaces will need 4-bit link indices. In general, the link or interface IDs of a node may be *locally hashed using a globally-known hash function*. Since every node knows the global hash function and it operates on globally-known link IDs (e.g.

IP addresses of interfaces) each node can independently compute the hashes of any other node. A path can now be



IP Address	Index
128.12.25.2	1
128.12.25.3	2
128.12.25.4	3
128.12.25.5	4

Fig. 2. Explanation of Index-Based Encoding Scheme

specified as a concatenation of such link-indices (e.g. Figure 2 shows PathID, in binary, of a path via nodes 9-10-6). This PathID encoding is guaranteed to be unique (unlike the earlier MD5+CRC32 encoding which had a very small collision probability).

The concatenation operation used here is an example of a *reversible* or perfect hash, i.e., the local hash (i.e. next-hop information) can be extracted from the overall PathID without needing a per-path table entry. The extra state needed at interior nodes is a small; only a table mapping link indices to link-IDs is needed. For example, at a router with 15 interfaces, a 15 entry index-table is needed irrespective of network size. No other control-plane computation or state-complexity is required at interior nodes. Since the interior nodes can forward to any neighbor now, a large number of network paths may be supported. Edge-nodes can compute paths using heterogeneous algorithms, and use a simpler validation algorithm (see Section II-C.2).

B. Packet Forwarding

This section describes the forwarding table structure and forwarding algorithm for various PathID encoding schemes in BANANAS. Section II-B.1 describes the forwarding corresponding to our canonical choice of hash function described in Section II-A. Section II-B.2 develops an alternative forwarding algorithm (for OSPF/IS-IS) when the reversible hash PathID encoding described in Section II-A.2 is used. Note that this scheme does not require a large forwarding table at interior nodes.

Figure 3 shows a partially upgraded network. Nodes A, C and D are multipath capable (MPC). Assume that node A is the originating node for a packet destined to node F. The shortest path from intermediate node B to node F is B-D-F and path A-B-C-F is not available for forwarding because node B is a non-upgraded node and the next-hop of default shortest path of B is not C. However, paths such as A-B-D-C-F, A-D-E-F, A-D-C-E-F etc. are available. If the path A-B-D-E-F is chosen, then the PathID of an incoming packet will be Hash(A-B-D-E-F). A sets the PathID

field to Hash(D-E-F), i.e. the hash of the path suffix from the next MPC router to destination. Node B forwards the packet on its shortest-path (i.e. to D). Node D sets the PathID to zero, because there is no MPC router on the path to F.

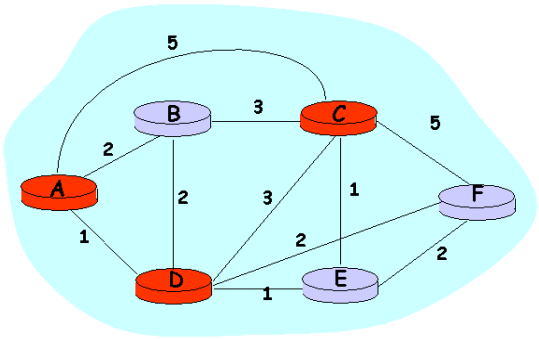


Fig. 3. Multi-Path Forwarding with Partial Upgrades

1) Canonical Scheme: IP forwarding tables essentially contain two-tuple entries of the form **[destination prefix, outgoing interface]**. Packet forwarding is based on a longest-prefix-match lookup to obtain the next-hop information. At BANANAS upgraded routers employing canonical hash for PathID encoding, we propose to use four-tuple entries of the form **[destination prefix, incoming PathID, outgoing interface, outgoing PathID]**. The "incoming PathID" field represents the hash of the explicit path from the current router to the destination prefix. The "outgoing PathID" field is the hash of the corresponding path suffix from the *next upgraded router* to the destination (See Section II-A for definition of).

An upgraded router first matches the destination IP address using the longest prefix match, followed by an *exact match* of the PathID for that destination. If matched, the incoming PathID in the packet is replaced by the outgoing PathID, and the packet is sent to the outgoing interface. If an exact match is not found (i.e. errant hash value in packet), then the hash value in the packet is set to zero, and the packet is sent on the default path (i.e. shortest path in OSPF/IS-IS or default policy route in BGP-4). The hash value may also be set to zero if the next-hop is the destination itself, or there are no upgraded routers in the path specified by the incoming PathID. A non-upgraded router simply ignores the PathID field and forwards the packet on the shortest path.

The global PathIDs may be computed at each router with minor modifications to OSPF LSAs (See Section III).

2) Index-Based Scheme: Packet Forwarding: Upgraded interior routers maintain an index table that maps the interface index to the link interface IP address. On receiving a packet, an upgraded interior router extracts the interface index of the outgoing interface (next-hop) from the PathID field in the packet header and uses the interface index table to forward the packet on the appropriate link (see Figure 4).

Figure 4 shows a packet being sent from node S to node 7 along the path S-6-2-4-3-7, the PathID at various points

and various interface indices. Only nodes S, 6 and 4 are upgraded. Node S has complete map of the network from the link-state database and knows that node 6 has two interfaces and the next-hop index at node 6 is 2, encoded using two-bits. Note that the interface indexing starts from 1 because PathID of zero still refers to the default (shortest) path. Likewise, the index at node 4 for this path is 3, encoded using three bits. The PathID of the packet sent from node S is $0...01110_2$ = 14, indicating an index ($10_2 = 2$ for node 6 and $011_2 = 3$ for node 4). Node 6 has an index table with 2 entries mapping the link indices to the interface IP addresses. On receiving a packet with PathID in the routing header, it extracts the last two bits and then looks up its index table. The PathID is also right-shifted by two bits in this operation so that the next upgraded router can extract its index from the last bits of the PathID. Similarly, node 4 will extract three bits from the PathID and right shifts it by the same number before forwarding it. The remaining PathID will now be zero. The non-upgraded routers merely forward packets along the default shortest paths, oblivious of the PathID field.

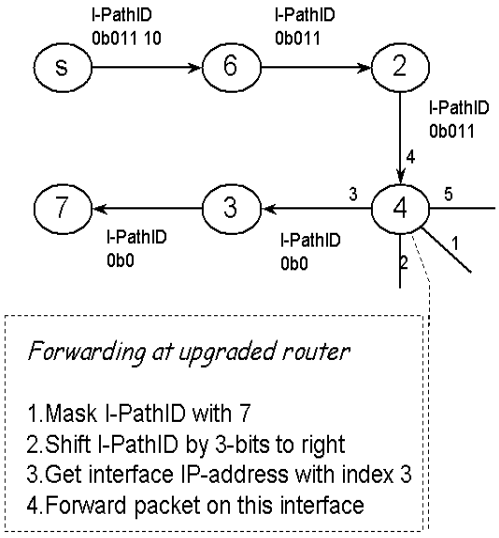


Fig. 4. Forwarding with the Index-based PathID encoding scheme (Note: “0b” indicates binary encoding)

C. Path Computation

In this section we discuss various path computation schemes that can be used in a partially upgraded BANANAS network. The BANANAS framework not only supports upgrades of a subset of nodes, but also allows heterogeneity in multipath computation algorithms used at different upgraded routers.

In link-state protocols each router has a complete map of the network in the form of link-state database. We propose to first annotate this “map” at an upgraded node with the knowledge of other upgraded nodes (we defer the discussion of how this is achieved in case of OSPF/IS-IS and BGP to sections III and IV). In Figure 3, upgraded node A will know that nodes C and D are upgraded and vice versa.

In this section, consider a single flat, link-state routing domain. We do not consider extension of BANANAS

to distance-vector routing algorithms (e.g. RIP). The extension of BANANAS to multi-area OSPF domains is discussed in Section III. Using the link-state database ("map") and knowledge of upgraded routers, every router can locally compute available network paths.

The BANANAS framework allows an upgraded router to compute and store all or a *valid subset of available paths* under partial upgrade constraints. The subset of available loop-free paths can be computed using any multipath computation algorithm available in literature, for example k-shortest-paths, all k-hop paths, k-disjoint paths (see [5] and references within), DFS with constrained depth ([7] uses a depth-constraint of 1-hop) etc. The only constraint is that the algorithm should also compute the shortest (default) path. This constraint arises because BANANAS router also sees packets without a PathID (the packets originating from non-BANANAS upgraded routers) or with a PathID that does not match its forwarding table. In these cases, the packet gets forwarded along the default shortest path. Note that even if the packet has already traversed the next hop of the shortest path, there will not be any loops because the next hop router will now forward the packet along the shortest path. Any multipath computation algorithm can be adapted for the constraint that there is a known subset of BANANAS upgraded routers.

1) Canonical Scheme: Path Computation: The simplest path computation algorithm is to compute all available paths under partial upgrades. The paths can be computed by performing a depth-first-search (DFS) [25] that traverses every neighbor of upgraded nodes and the shortest-path neighbor at non-upgraded nodes. The shortest path next-hops of non-upgraded nodes can be found by performing multiple Dijkstra's or an all-shortest paths algorithm e.g. Floyd-Warshall [25]. This results in a table containing next-hops for all paths to a destination under the constraint of a known subset of MPC nodes. We refer to this strategy as DFS under partial upgrade constraints or DFS-PU for shorthand. This simple approach is expensive in speed, computational and space complexity. Number of available paths increases exponentially with the number of MPC routers.

However, if different routers compute and store different sets of paths and the canonical PathID encoding scheme is used, it is possible that the path computed by one upgraded router may not be supported by another upgraded downstream router. A path is defined to be *invalid* if forwarding support for the path does not exist at some downstream router along the path.

To solve the above problem, we propose a *distributed validation algorithm* that ensures validity of paths. The main idea behind the validation algorithm is that a path is valid (i.e. forwarding for a path exists) if all its path suffixes are valid. This suggests a mathematical induction based approach. All one-hop paths are always valid because they represent a direct link. A two-hop path is valid if its one-hop path *suffix* is valid.

The proposed algorithm (see Algorithm 1) has two phases. In the first phase a node computes the paths using the chosen algorithm. For example, let us assume that node i uses a k_i-shortest-path algorithm. The k_i paths computed to each destination are input into a map data structure that is ordered by hop-count. In phase 2, the validation phase, the node needs to know the path computation algorithm and parameters used by other upgraded nodes. In our example, node i needs to know the k_j parameter associated with each upgraded node j. With this knowledge, it can compute the k_j paths for node j and input it into the hop-count ordered map data-structure (lines 2-5 in Algorithm 1). At non-upgraded nodes, k_j is 1 (lines 6-9 in Algorithm 1). Essentially we have computed all

Algorithm 1 Algorithm for validating paths at a router in a partially upgraded network

```
1: Let NU and U denote the set of all non-upgraded and upgraded nodes respectively
2: for all u ∈ U do
3:    newPaths ← Compute paths using u's advertised algorithm
4:    Routing_Map.append(newPaths)
5: end for
6: for all n ∈ NU do
7:    newPaths ← Compute shortest path using Dijkstra's algorithm
8:    Routing_Map.append(newPaths)
9: end for
10: All 1-hop paths are valid
11: Initialize suffixLength ← 2
12: while suffixLength < maxHops do
13:    for all path ∈ Routing_Map do
14:       if hop count of path ≥ suffixLength then
15:          temp_pair.hopcount ← suffixLength-1;
16:          temp_pair.PathString ← last suffixLength nodes in path;
17:          if Routing_Map.find(temp_pair) == FALSE then
18:             delete path
19:          end if
20:       end if
21:    end for
22:    suffixLength++;
23: end while
```

potentially *available* paths in phase 1.

Phase 2 operates similar to mathematical induction. All one-hop paths in the map are declared as valid. For each 2-hop path, the algorithm simply searches for the 1-hop path suffix in the just-validated set. If a match is not found, the path is invalid and is discarded. If the path (i.e. the corresponding PathID entry) exists in the forwarding table, it is removed. In this process, validating an m-hop path entry implies looking up its (m-1)-hop path suffix in the just-validated set of (m-1)-hop paths and finding a match (the variable temp_pair and the lines 16,17 in Algorithm 1 are used to find a suffix match in the Routing_Map structure). By mathematical induction, when the entire map has been linearly traversed, the remaining paths are valid.

The computational complexity of this approach can be estimated as follows. In a N-node network with u upgraded routers, the complexity of first phase is given $uC(k) + (N-u)C(1)$ where, $C(k)$ denotes the complexity of computing k-shortest paths, $C(1)$ denotes the complexity of Dijkstra's algorithm. The total number of paths, T, computed at the end of first phase is equal to $(N-1)((N-u) + \sum_{i=1}^{i=u} k_i)$. The complexity of the validation phase is $O(Tlog(T)\bar{h})$ where, $\bar{h}$ is the average hop count for the paths. The log(T) term arises due to searching for a suffix in the Map (see Algorithm 1, line 18). The validation algorithm may be optimized or be eliminated for

special cases, e.g. if all nodes are upgraded and use the same value of k.

In summary, Algorithm 1 is a general 2-phase validation procedure that can be applied to validate paths computed using *any* deterministic path computation algorithm at MPC routers that also computes the default shortest path.

2) Index-based Scheme: Path Computation: In this scheme, "source" (or edge routers) can independently use any multipath computation algorithm to find a subset of available paths, similar to the discussion in Section II-C. The only information needed is the knowledge of which routers in the network are upgraded (using the MPC-bit in LSAs).

Algorithm 2 Algorithm for validating paths in the index-based Scheme

```
1: Let 𝒩 denote the set of nodes in a network and 𝒩𝒰 denote the set of non-upgraded nodes
2: Compute multiple paths using desired multipath computation algorithm
3: Let 𝒫(dst) denote the set of paths to destination dst
4: for n ∈ 𝒩𝒰 do
5:    Compute Dijkstra
6: end for
7: for dst ∈ 𝒩 do
8:    Compute the desired paths to destination dst using any of k-shortest paths, k-disjoint paths, all paths upto k-hops etc.
9:    for path ∈ 𝒫(dst) do
10:      for n ∈ 𝒩𝒰 do
11:         if path.find(n)==TRUE then
12:            // nextHopSP is the next-hop in the shortest path from n to dst
13:            // nextHop(path) denotes the next-hop of n in the path
14:            if nextHop(path) ! = nextHopSP then
15:               delete path
16:            end if
17:         end if
18:      end for
19:   end for
20: end for
```

Path validation is only necessary to impose the constraint that non-upgraded nodes can forward packets only on their default shortest paths. Algorithm 2 shows the pseudo-code of a generic validation algorithm for edge routers. Only those paths are valid, where the next-hop of the non-upgraded routers corresponds to their shortest path next-hop. Again, the validation algorithm consists of two phases. First phase deals with the computation of shortest paths for non-upgraded nodes (lines 4-6 in Algorithm 2) and computation of multiple paths using any desired multipath computation algorithm. In second phase, the paths are checked for passing through non-upgraded nodes. If a path passes through a non-upgraded node, the next-hop must be same as the next-hop in the pre-computed shortest path. A path is *invalid* if this condition is not met (lines 14-16). In a N-node network with u upgraded routers, the complexity of first phase is given $C(k) + (N - u)C(1)$ where, $C(k)$ denotes the complexity of computing k paths (assuming the upgraded router keeps k paths), $C(1)$ denotes the complexity of Dijkstra's single-shortest-

path algorithm. The complexity of the second phase of the validation algorithm is $O(k \times (N-1) \times (N-u))$, where k is the maximum number of paths for each destination to be stored in the forwarding table. Note that the validation phase in the index-based path encoding scheme is simpler compared to the validation phase in Algorithm 1. This is because the upgraded routers can forward packets to any of their interfaces. Recall that in Algorithm 1, the validation phase also needed to ensure that the downstream *upgraded* nodes of a path would indeed provide forwarding for that path (i.e. have a forwarding table entry for that path).

D. Comments on Overheads

In this section we analyze various overheads associated with enabling explicit, multipath routing using BANANAS.

BANANAS requires a per-packet PathID field in the packet header. In the canonical scheme, a 32-bit PathID hash is included in every packet. A hash-based data-plane encoding is more efficient than IPv4/IPv6's loose-source-routing encoding [19], [20] that is an uncompressed string of IP addresses. Moreover, 32-bit per packet PathID overhead is not substantial when compared to 128-bit IP addresses in IPv6. For enabling BANANAS end-to-end in the Internet across multiple ASes, we propose fields i-PathID, e-PathID and address stack (discussed in Sections III and IV-C).

In the index-based scheme, the computational and space complexity at the core routers is traded off for increased per packet overhead. For a reasonable maximum bit-budget in the packet header (e.g. 128 bits), and an average of 15 interfaces per router, up to 32-hop paths can be encoded with this technique. In [26], authors have found that the average number of hops to reach a destination in the Internet is 19. The limitation of 32-hops is not too restrictive as it applies only within a single area or a domain. The PathID is re-initialized by the first upgraded router of an area after crossing any area or domain boundary.

Note that depending on the choice of hash function, PathID collision may occur. Note that in BANANAS, since forwarding is done using longest prefix destination IP address match followed an exact PathID match, a collision occurs only when multiple paths to the same destination have the same PathID. As opposed to forwarding based on exact PathID match, this scheme reduces the collision probability by O(N^2), where N is the number of nodes in the network. The canonical scheme uses a combination of low-collision probability MD5 and CRC hash, thus reducing the chances of collision even further. An analysis of the collision probability for the canonical scheme was presented in Section II-A. In the index-based scheme, PathID is a string of globally known unique indices. Thus, under stable conditions there is no probability collision in the index-based scheme.

Today OSPF uses a single, shortest path routing with equal cost multipath. The Dijkstra's shortest path algorithm is used to compute shortest paths from a router to all other routers in the area. For enabling multipath routing, a multipath computation algorithm must be used. Depending on the multipath computation algorithm, a higher overhead is incurred. In the canonical scheme, all the routers supporting BANANAS must compute multiple paths and validate them. In case of k-shortest paths, the complexity of path computation and validation algorithms for the canonical scheme is discussed in Section II-C.1. In the index-based scheme, core routers do not need to compute

multiple paths, only edge/source routers need to compute and validate multipaths. However, the complexity of the validation algorithm is substantially reduced as a BANANAS upgraded router supporting index-based scheme can forward an incoming packet on all possible interfaces. The complexity of the validation algorithm for the index-based scheme was discussed in Section II-C.1.

Note that in any multipath routing scheme a memory overhead will be incurred depending on number of extra path information in the forwarding tables of a router. This is true for the BANANAS canonical scheme. However, the index-based scheme does not require all routers to store additional entries in the forwarding tables. Only the edge routers are required to keep additional entries. However, a index-table of the O(number of outgoing interfaces) is required for the packet forwarding.

To summarize the impact of index-based scheme in terms of function placement and complexity management, the index-based scheme uses per-hop *PathID processing* instead of a table-driven per-hop *PathID swapping* strategy. Only edge routers need to compute the multipaths and their PathIDs using a simplified validation procedure. The memory overhead requirements at the core routers are also greatly reduced (O(number of interfaces) as compared to O(number of nodes)).

Moreover, the scheme is only applicable to link-state protocols, where the neighbor relationships do not change often. Specifically, the index-based scheme is *not* applicable to path-vector based protocols like BGP-4, or mobile ad-hoc networks where neighbor relationships change rapidly. The fundamental tradeoff in BANANAS (given our canonical choice of PathID hashing method) is a per-packet overhead, route-computation and space complexity incurred at upgraded routers to achieve multiple path routing while avoiding signaling.

III. BANANAS Extensions For Intra-Domain Protocols

In this section, we summarize the extensions to OSPF/IS-IS to support the BANANAS framework. A 32-bit PathID field is required in the packet header, that can be implemented as a new *routing option*, called *i-PathID* (in the context of intra-domain routing, PathID actually refers to i-PathID). The route computation algorithm (Dijkstra's algorithm) at upgraded routers must be extended to compute multiple paths (e.g. DFS under partial upgrade constraints (DFS-PU), k-shortest paths [5] etc), and a validation algorithm (Algorithm 1). The upgraded nodes must compute the shortest path as the default path. Incoming packets with erroneous PathIDs are forwarded on the shortest paths and the PathID field set to zero. The intra-domain forwarding tables at upgraded routers would have tuples *(destination prefix, incoming PathID, outgoing interface (next-hop), outgoing PathID)*. As indicated in Figure 5, one bit in the OSPF Link State Advertisements (LSAs) [27] must be used to indicate that the router is multipath capable (MPC). In the Linux/Zebra based implementation as well as in the SSFNet simulations, we have used the eighth bit in the *LSA options* field of the router-LSA as the MPC bit.

Also, if we allow different upgraded routers to compute paths using different algorithms, we need some bits to indicate the choice of route computation algorithm along with its parameters (E.g. the value of k in k-shortest paths algorithm). In our Zebra-based implementation, we have assumed that upgraded nodes implement the k-shortest-

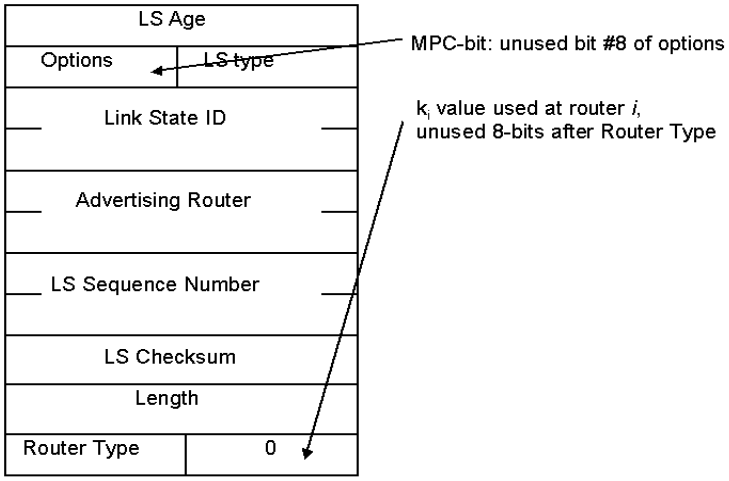


Fig. 5. Proposed Modifications to OSPF Link State Advertisements (LSAs)

path algorithm with different values of k. Therefore, we leverage the currently unused 8-bits after the router type field in the LSA to indicate the value of k.

For the alternative index-based path encoding scheme, the concatenation of indices is done from the lower-order-bits to the high-order-bits. Each router simply shifts the PathID to the right by the number of bits needed to encode its interface index. This allows upgraded *interior* routers to extract the next-hop index from the lowest-order-bits without knowing its position within the path, i.e. without the knowledge of how many upgraded nodes are on the path. The upgraded interior routers only need to set the MPC bit in their LSA and need not advertise the route computation algorithm. Each upgraded router must maintain an ordered list of its own interfaces and the corresponding index. The upgraded *edge* routers can use any multipath algorithm to compute multiple paths. However, they need to validate the paths using the validation algorithm (Algorithm 2). All upgraded routers must always compute the default shortest paths to all destinations. This is necessary in order to forward packets with no PathID option, zero or erroneous PathID.

A. Forwarding Across Multiple Areas

Large OSPF and IS-IS networks support hierarchical routing with up to two levels of hierarchy. Our approach is to view each area as a flat routing domain for the purpose of multipath computation. Multiple paths are found locally within areas, and crossing areas are view as crossing to a new multipath routing domain, i.e. we re-use the i-PathID field. For example, if a source needs to send a packet outside an area, it chooses one of the multipaths to the area border router (ABR). Then, the ABR may choose among the several multipaths within area 0 to other ABRs. The i-PathID field is re-initialized by the first ABR at the area-boundary.

IV. *BANANAS* EXTENSIONS TO BGP

A. Motivation and Goals

BGP-4 [28] is *the* inter-domain routing protocol in the Internet. BGP uses a path vector and policy routing approach to announce a subset of actively used paths to its neighbors. Load-balancing and traffic engineering in BGP are becoming important as operators attempt to deploy services like virtual private networks (VPNs), and optimize on complex peering agreements [1], [29], [30], [31]. Enterprises are also increasingly multi-homed and are increasingly active in managing their inbound and outbound traffic [1], [32].

While BANANAS is not designed to address multitude of configuration, stability and load-balancing problems [33], [30], [34] of BGP, it does provide a set of building blocks to enable fine-grained BGP traffic engineering both within and across domains. In particular, BANANAS introduces two new capabilities: *explicit exit* forwarding and *explicit AS-PATH* forwarding. We examine these aspects further in the following sections.

B. Explicit-Exit Forwarding

The idea of explicit-exit routing is quite simple. The overall objective is to define a traffic aggregate and then map it to a chosen exit router (ASBR). Traffic aggregates may be chosen at per-packet, per-flow or per-prefix granularities by the upgraded EBGP or IBGP routers, i.e., ISPs can define fine-grained bundles of outbound traffic. Unlike LOCAL_PREF, the explicit exit capability can map traffic for the same destination prefix to multiple exits (based upon the autonomous decisions at upgraded IBGP nodes).

The explicit exit mechanism works as follows. An upgraded IBGP router chooses an arbitrary exit AS border router (ASBR) for a given traffic aggregate (e.g. a flow or all traffic to a destination prefix). It then "pushes" the destination address into a *"address stack"* field, and replaces the destination address with the exit ASBR address (adjusting the checksum appropriately). Now, intermediate routers forward the packet to the exit-ASBR to which it is addressed. The exit-ASBR then simply "pops" the address from the address-stack field back into the destination address field (and adjusts the checksum) before forwarding it along to the next AS.

The upgraded IBGP node would hence have table entries of the form: **[Dest-Prefix Exit-ASBR Next-Hop-to-Exit-ASBR]** and **[Dest-Prefix Default-Next-Hop]**. The second tuple is the regular IBGP-defined default policy route for the destination prefix: this forwarding entry is used for all traffic for which this IBGP router does not decide the exit router. The first 3-tuple is applied only to the traffic aggregates for which this IBGP router chooses an explicit exit. This kind of operation is important to avoid conflicting exit routing decisions by upgraded IBGP routers.

Observe that only *a subset* of IBGP routers and exit ASBRs (eBGP) routers need to be upgraded. All BGP routers synchronize on their default policy routes as usual [28]. In addition, the upgraded exit ASBRs should also synchronize with the upgraded IBGP routers so that they know which exits are available for any given prefix.

The explicit-exit mechanisms proposed are similar in spirit to the label-stacking (multi-level tunnelling) ideas in MPLS[22]. A key difference is that BANANAS proposes only a single-level address stack, whereas MPLS can

have multiple levels in its label-stack. Note that the explicit exit routing is a special case of explicit path routing introduced in earlier sections. The PathID "hash" in this case is simply the exit ASBR IP address. This address stacking procedure operates in the fast processing path at all routers (both upgraded and non-upgraded), unlike IP loose-source-routing that defaults to the slow-processing path because it is an IP option.

C. Explicit AS-PATH Forwarding

The goal of explicit AS-PATH forwarding is to provide a distributed mechanism to send packets along an arbitrary, but validated AS-PATH. The idea is similar to the explicit path routing introduced for OSPF/IS-IS, except that we now refer to explicit AS-PATHs rather than a sequence of contiguous routers and links. In particular, we propose a separate hash field called external-PathID or e-PathID in packets for this function. The e-PathID is the hash of the desired AS-PATH, i.e., hash of the sequence of AS numbers.

The e-PathID hash is processed as follows. First, in an upgraded AS, assume that at least the entry and exit AS border routers (ASBRs) are upgraded to support the explicit AS-PATH function. Assume that a border router (called the entry ASBR) receives a packet with a non-zero, valid e-PathID. The incoming e-PathID is used by the entry ASBR to determine an appropriate exit ASBR. The packet is then explicitly sent to this exit ASBR using the mechanisms described in the earlier section, i.e. address-stacking. Indeed, once the address is stacked, the i-PathID may also be explicitly chosen to indicate a specific route to that exit ASBR. Note that the e-PathID is *not* swapped at the entry ASBR. The outgoing e-PathID (for the AS-PATH suffix) replaces the incoming e-PathID only at the *exit* ASBR. This convention is required because the autonomous system is an atomic entity (similar to a node) as far as the e-PathID is concerned. However, the AS physically breaks up into an entry- and exit-ASBR (similar to input and output interfaces of a node). If we imagine that the abstract PathID swapping happens at the output interface, that corresponds to our convention of swapping the e-PathID at the exit ASBR. Observe, that we have required only EBGP routers to be aware of the multi-AS-PATH feature, and do not require upgrades in selected IBGP routers (unlike the explicit exit case discussed earlier).

To illustrate the explicit AS-PATH feature, we consider the AS-graph topology in Figure 6, and assume that we would like to send traffic from AS1 to AS5, i.e. to the IP prefix 0.0.0.48 along AS-PATH AS1-AS2-AS3-AS5, represented as (1 2 3 5). The AS-PATHs available are AS1-AS2-AS5, AS1-AS2-AS4-AS3-AS5, AS1-AS2-AS3-AS5. The explicit path (1 2 3 5) is chosen at router 1; the suffix AS-PATH is (2 3 5) whose hash is placed in the e-PathID field in the outgoing IP packet. The next-hop is an entry router in AS2. An exact match of prefix and e-PathID results in the packet being forwarded to the AS3. The e-PathID will be swapped only at the exit ASBR (i.e. Router 2 in AS2). A similar sequence of events occurs in AS3 involving entry ASBR (router 1) and exit ASBR (router 3) before the packet is forwarded to AS5. The outgoing e-PathID from AS3 will be set to 0 because AS5 is the destination AS.

In spite of these apparent reductions in upgrade complexity, BGP's path-vector nature poses a more important problem. Specifically, a new AS-PATH is unknown to an upstream AS unless the intervening AS explicitly advertises it (after internal synchronization). In other words, even if ISPs were interested in AS-PATH multiplicity,

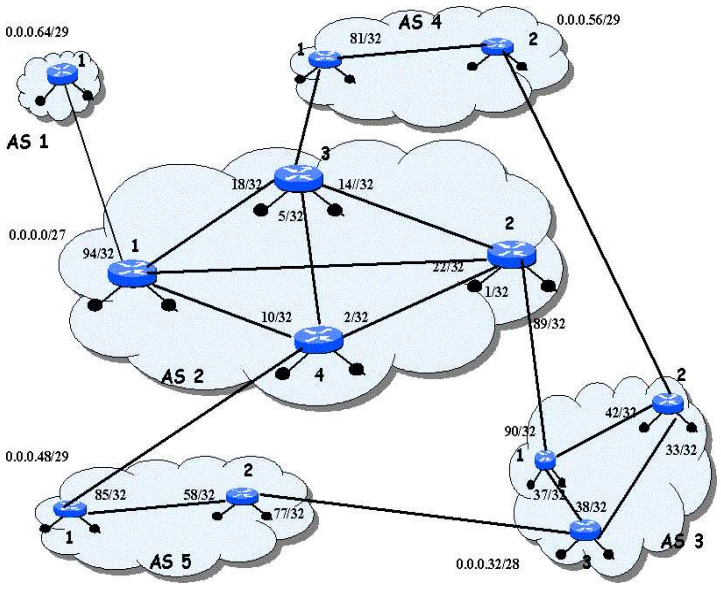


Fig. 6. Topology for illustrating explicit AS-PATH forwarding

increased control traffic is necessary to advertise the existence of multiple AS-PATHs to neighbor AS'es. Recall that such excess control traffic was not required in link-state algorithms (we merely piggybacked LSAs with minimal information). On the other hand, the path-vector nature of BGP-4 also implies that no path computation is necessary once the multiple AS-PATHs have been received and filtered for acceptance.

We recognize that this increased control traffic requirement poses a significant disincentive for ISPs against adopting multi-AS-PATH capabilities en masse. Given the scalability and instability issues with adding control traffic, we expect that ISPs may choose to advertise only a small set of multiple AS-PATHs to their neighbor AS'es. For example, some AS'es may collaborate to allow forwarding along multiple paths to certain destination prefixes and advertise this as a non-transitive attribute to certain AS'es only.

D. BANANAS Extensions to BGP-4

In summary, we propose two capabilities in the context of inter-domain routing: *explicit exit routing and explicit AS-PATH routing*. For the former, we propose a 32-bit "address stack" field in the routing header into which the destination IP address will be *"pushed"*. The destination field in the IP header is overwritten with the exit ASBR's IP address. The Exit ASBR will simply *"pop"* the destination address back from the "address stack" to the destination IP address. This address stacking procedure (similar to MPLS) operates in the fast processing path unlike the IP loose source routing option. Moreover, it allows flexibility for only a subset of BGP routers to be upgraded to support such explicit exit choice.

For explicit AS-PATH forwarding we propose a new 32-bit field in the packet routing header called the external PathID or e-PathID. This field stores a hash of the sequence of ASNs along the desired explicit AS-PATH. ISPs may choose to only advertise a small set of multiple AS-PATHs to their selected neighbor AS'es. In a multi AS-

PATH capable AS, only the entry ASBRs and exit ASBRs (i.e. only the EBGP routers) need to be upgraded and synchronized on the available multiple AS paths. The incoming ePathID hash is swapped with the outgoing AS-PATH suffix hash only at the exit AS border router. The forwarding from the entry ASBR to the exit ASBR uses the explicit exit mechanisms described above. Multiple paths between the entry and exit ASBRs are possible using the i-PathID mechanism described earlier for intra-domain routing.

V. Implementation and Simulation Results

In this section, we illustrate the working of the proposed framework. We have implemented the BANANAS framework schemes in the Linux kernel: we use MIT's Click Modular Router package [35] (data-plane) and GNU Zebra routing sofware version 0.92a [36] (control-plane). These implementations are tested on Utah's Emulab testbed [37] to emulate sizable topologies running real implementation code. In particular, we test three cases: a) when an upgraded router keeps all available paths (as computed by the DFS-PU strategy), b) when upgraded nodes compute k-shortest paths, with heterogeneous values of k at different nodes, and c) the index-based scheme to illustrate architectural flexibility.

We use SSFNet [38] for larger integrated BGP/OSPF simulations. These SSFNet simulations illustrate the framework in larger network topologies that integrate both OSPF and BGP BANANAS functionalities. Note that in this section, we have intentionally preferred simplicity in terms of topology/test-case choices. We have performed a larger set of SSFNet simulations and Emulab runs in more complex scenarios, all of which support our assertions. These results will be reported in a detailed technical report.

A. Linux Implementation Results

Figure 7 shows the topology of a simple validation experiment conducted on Utah's Emulab [37] testbed with the Linux Zebra version 0.92a of OSPF (i.e. control-plane) upgraded with our BANANAS building blocks. The forwarding plane was implemented in Linux using MIT's Click Modular Router package [35]. Note that this is a partially upgraded network: only nodes 1 and 2 (the dark colored nodes) are upgraded in this configuration. Figure 7 also indicates the IP addresses of various router interfaces and the link weights. The router ID is statically defined to be the smallest interface IP address.

1) All Paths with Partial Upgrades (DFS-PU Algorithm): Table I illustrates a partial forwarding table computed at node 1 (IP address 192.168.1.1) for destination 3 (192.186.3.3). Note that the path string shown in Table I is only for the sake of illustration and is not stored in the actual routing table. The PathIDs are the (MD5 + CRC-32) hashes of the router IDs (i.e. IP addresses of nodes) on the path. For example, the PathID 2084819824 corresponds to a hash of the set of router IDs {192.168.1.1, 192.168.1.2, 192.168.6.6, 192.168.39.9, 192.168.3.3 }. The outgoing path ID is the hash of the suffix path formed after omitting 192.168.1.1. If the path goes through other nodes which are not upgraded (e.g. 1-4-3), the outgoing path ID is the hash of the suffix path starting from the next upgraded router on the path. In the case of the path 1-4-3, both nodes 4 and 3 are not upgraded, so the suffix path ID is zero.

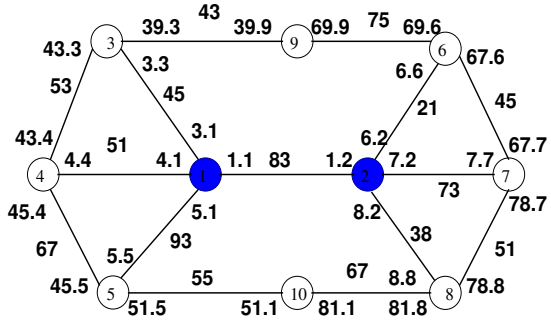


Fig. 7. Experimental Topology on Utah Emulab using Linux Zebra/Click Platforms (Note: only dark colored nodes are multi-path capable)

Outgoing I/f	Path	Incoming PathID	Outgoing PathID
192.168.1.1	1-2-6-9-3	2084819824	664104731
192.168.3.1	1-3	599270449	0
192.168.4.1	1-4-3	4183108560	0
192.168.5.1	1-5-4-3	1365378675	0

TABLE I

PARTIAL ROUTING TABLE AT 192.168.1.1 FOR DESTINATION 192.186.3.3

2) k-Shortest Paths with Partial Upgrades: In this section we illustrate, using the Linux implementation, the case when the upgraded routers compute upto k-shortest paths, and different upgraded routers using different values of k.

Consider the 10-node topology shown in Figure 7. This topology was setup in the Emulab network. We assume that the routers 192.168.1.1 and 192.168.1.2 are upgraded with k equal to 3 and 2 respectively. The results are presented to verify the correctness of the "validation phase" (Algorithm 2). Tables II, III show respectively part of the routing tables at 198.168.1.1 for destinations 198.168.6.6 and 198.168.8.8 respectively. Tables IV, V show the corresponding entries at router 198.168.2.2. For destination 198.168.6.6 the router 198.168.1.1 finds 3 paths, all of which are valid as two paths have next-hop 198.168.2.2 and router 198.168.2.2 keeps 2 shortest paths. For destination 198.168.8.8, the router 198.168.1.1 computes 3-paths, 1-2-8, 1-2-6-7-8, 1-2-7-8. The path 1-2-7-8 is invalidated in the "validation phase" as router 198.168.2.2 only keeps 2 paths (2-8, 2-6-7-8). Note that the *Path* string is shown in Tables II-V for the purpose of explanation.

B. Evaluation of Index-based Path Encoding Scheme

The alternative index-based PathID encoding scheme was implemented in the Linux kernel (MIT's Click Router platform) and simulated in SSFNet. We present our simulation results in this section on a sizeable topology that corresponds to the old MCI topology of 1995 [39].

Path	Incoming PathID	Next-hop	Outgoing PathID
1-2-6	1989316858	192.168.1.2	3491782861
1-2-7-6	656924081	192.168.1.2	3645081405
1-3-9-6	534784006	192.168.3.3	0

TABLE II

PART OF ROUTING TABLE AT 192.168.1.1 FOR DESTINATION 192.186.6.6

Path	Incoming PathID	Next-hop	Outgoing PathID
1-2-8	3654096761	192.168.1.2	1973392862
1-2-7-6-8	1777786090	192.168.1.2	2123671348

TABLE III

PART OF ROUTING TABLE AT 192.168.1.1 FOR DESTINATION 192.186.8.8

In this configuration, only nodes 4, 6, 7, 9, 10 are upgraded. The source node in this simulation is node 6. Observe that node 6 is the only node that computes the k-shortest-paths (k = 5) for all destinations and runs the validation algorithm (Algorithm 2). All other upgraded nodes merely keep an index table as described in Section II-A.2). Table VI shows a part of the forwarding table at node 6 (only those paths for destination node 7), and the i-PathIDs using index-based encodings. The node 6 may choose any one of these paths for a packet to node 7. We have verified that the progression of i-PathIDs through the network follows the description given in Section II-B.2.

C. Integrated OSPF/BGP SSFNet Simulation

In this section we use SSFNet simulation results to illustrate the integrated operation of proposed framework in the Internet. This example demonstrates both the intra-domain (OSPF) and inter-domain (BGP-4) operation of the framework with explicit AS-PATH as well as explicit exit forwarding.

Figure 9 shows the topology used for the results presented in this section. The topology has eight (8) autonomous

Path	Incoming PathID	Next-hop	Outgoing PathID
2-6	1973392862	0.0.0.0	1973392862
2-7-6	2123671348	192.168.7.7	2123671348

TABLE IV

PART OF ROUTING TABLE AT 192.168.2.2 FOR DESTINATION 192.186.6.6

Path	Incoming PathID	Next-hop	Outgoing PathID
2-8	3491782861	0.0.0.0	0
2-6-7-8	3645081405	192.168.6.6	0

TABLE V

PART OF ROUTING TABLE AT 192.168.2.2 FOR DESTINATION 192.186.8.8

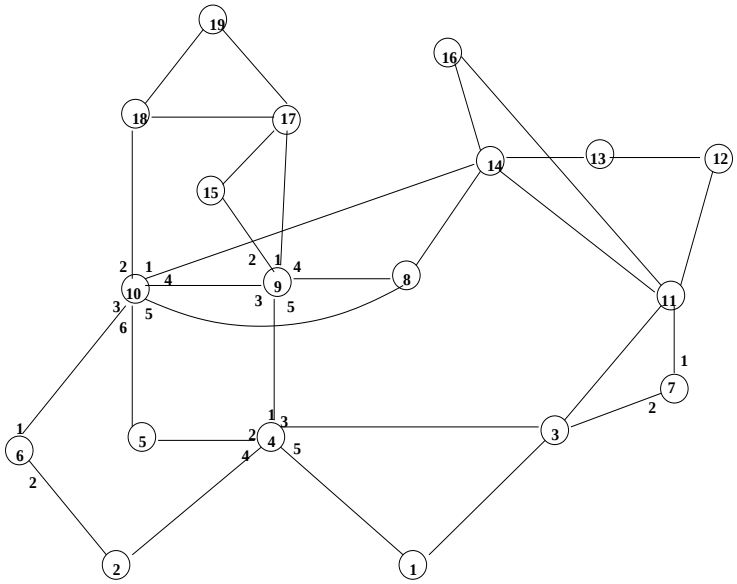


Fig. 8. Old MCI Topology: Used for Testing the Index-Based Scheme (Only Nodes 4, 6, 7, 9, 10 are upgraded)

Path	Next-Hop	i-PathID
6-2-4-3-7	2	0b01110
6-10-9-17-16-11-7	10	0b00110001
6-10-14-11-7	10	0b00101
6-10-9-4-3-7	10	0b01110110001

TABLE VI

PATHS AT NODE 6 FOR DESTINATION NODE 7 (NOTE: 0B INDICATES BINARY ENCODING)

Forwarding Table of AS1 at Router 1					
Dest	NextHop	In e-PathID	AS-PATH	Out e-PathID	Exit ASBR
0.57/28	**2.93/32**	**2025862315**	**2-4-8**	**3535826417**	**0.91/32**
0.57/28	2.93/32	4160716901	2-5-6-7-8	1248156781	0.91/32
0.57/28	2.93/32	669121903	2-5-6-4-8	2630971039	0.91/32

TABLE VII

INTEGRATED OSPF/BGP SIMULATION: FORWARDING TABLE OF THE BORDER ROUTER IN AS1 (NOTE: 0.57/28 REFERS TO IP ADDRESS 0.0.0.57/28 ETC)

systems (AS'es). Four of these AS'es, namely AS1, AS2, AS5 and AS6, have been upgraded to support explicit AS-PATH forwarding. Even within these upgraded autonomous systems, only a *subset* of routers are upgraded to support the explicit AS-PATH and explicit exit routing as described in Sections IV-C and IV-B. The upgraded routers have been marked with a "U" in Figure 9. A blow-up of the internal topology of AS2 is shown in Figure 10;

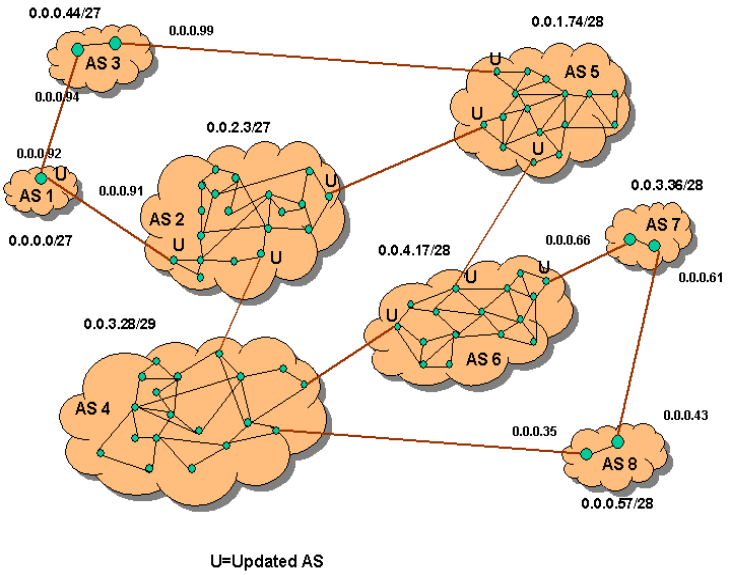


Fig. 9. Topology used for integrated SSFNet simulation

Forwarding Table of AS2 at Router 5					
Dest	NextHop	In e-PathID	ASPATH	Out e-PathID	Exit ASBR
0.57/28	**2.97/32**	**3535826417**	**2-4-8**	**3535826417**	**2.107/32**
0.57/28	2.113/32	3535826417	2-4-8	3535826417	2.107/32
0.57/28	2.97/32	1248156781	2-5-6-7-8	1248156781	2.24/32
0.57/28	2.113/32	1248156781	2-5-6-7-8	1248156781	2.24/32

TABLE VIII

INTEGRATED OSPF/BGP SIMULATION: FORWARDING TABLE ROUTER 5 IN AS2 (SEE FIGURE 10)

the upgraded routers are again indicated with “U”

Consider forwarding of a packet from AS1 to AS8 (see Figure 9). Given the constraints that only a partial set of AS’es are upgraded, the following AS-PATHs may be used from AS1 to reach AS8: AS2-AS4-AS8, AS2-AS5-AS6-AS7-AS8 and AS2-AS5-AS6-AS4-AS8. These AS-PATHs and their corresponding e-PathIDs are indicated in Table VII, which is a part of the routing table at the AS border router in AS1. Note that the AS-PATH AS2-AS4-AS6-AS7-AS8 is not available because AS4 is not upgraded, and uses a default AS-PATH of AS4-AS8. Also in this simulation, we assumed that the upgraded routers do not do any further filtering, i.e., they re-advertise all their available AS-PATHs to their neighboring AS’es.

In our example simulation, the border router of AS1 chooses the AS-PATH AS2-AS4-AS8, which corresponds to the e-PathID of 3535826417 (see the first row of Table VII). When the packet arrives at router 5 of AS2 (the entry ASBR), its header looks like Figure 11(A). This entry ASBR (i.e. router 5) of AS2 examines the incoming

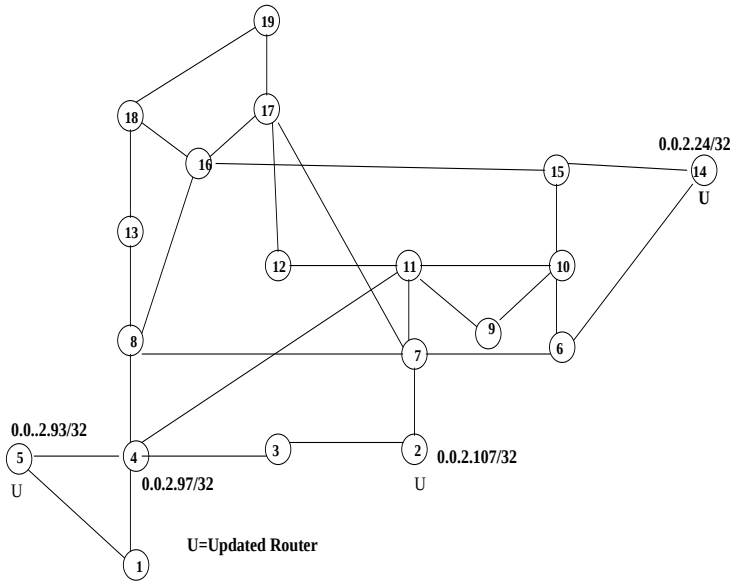


Fig. 10. Blow-up of AS2's Internal Topology in the Integrated OSPF/BGP Simulation (Figure 9)

Destination	Path	i-PathID
0.0.2.107/32	5-4-3-2	17
0.0.2.107/32	5-1-4-3-2	18
0.0.2.107/32	**5-4-11-7-2**	**1669**
0.0.2.107/32	5-4-8-7-2	201
0.0.2.24/32	5-4-11-10-15-14	69
0.0.2.24/32	5-4-8-7-6-14	169
0.0.2.24/32	5-4-8-16-15-14	105
0.0.2.24/32	5-1-4-8-16-15-14	106
0.0.2.24/32	5-4-11-9-10-15-14	101
0.0.2.24/32	5-1-4-11-9-10-15-14	102

TABLE IX

FORWARDING TABLE AT ROUTER 5 IN AS2 (FIGURE 10): K SHORTEST PATHS (K = 7)

e-PathID to find the exit ASBR to be node 2 with IP address 0.0.2.107 (see first row of Table VIII). Note that it *does not* swap the e-PathID field, because this will be done at the exit ASBR. To emphasize this point, observe that the outgoing e-PathID column in Table VIII is the same as the incoming e-PathID for the destination prefix 0.0.0.57/28.

The entry ASBR (router 5) now "pushes" the destination IP address (i.e. 0.0.0.57) into the address stack field and replaces it with the exit ASBR IP address. The entry ASBR also chooses a path within the AS to the exit ASBR. Table IX shows the intra-domain paths available to reach exit ASBR (router 2). In this simulation, we have integrated the index-based PathID encoding scheme as well as the k-shortest path route computation scheme (k=7) with the OSPF protocol running in AS2. In particular, the path 5-4-11-7-2 within the AS is chosen that corresponds

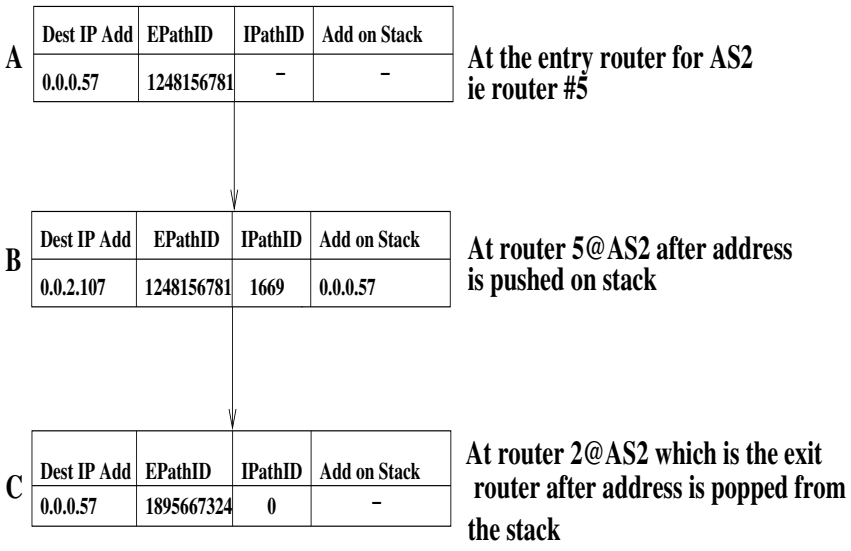


Fig. 11. Diagram Showing How e-PathID, i-PathID and Destination Address Change in the Integrated OSPF/BGP Simulation

to a i-PathID of 1669 (see the third row of Table IX). The header fields of the packet at this stage are shown in Figure 11(B).

The packet proceeds on the explicit intra-domain path (as described in earlier sections) to reach the exit router 2 with an i-PathID value of 0. At this router, the destination address (0.0.0.57) is "popped" back from the address stack. The e-PathID is also replaced with the outgoing e-PathID of 1895667324 (see Figure 11(C)). Now the packet is sent to AS4, which is not upgraded, but sends the packet on its default policy AS-PATH, i.e., directly to AS8. In summary, we have shown how a distributed set of upgraded and non-upgraded nodes, with explicit paths independently selected within upgraded AS'es can honor an explicit AS-PATH request of the source AS.

VI. Related Work

This high-level model is a *best-effort path multiplicity* model, clearly different from IPv4/IPv6 connectionless loose-source-routing model [19], [20] and from end-to-end signaled source-route models used in ATM networks (e.g. PNNI [21]) or MPLS networks [22].

Most related work for multipath routing have been done in the context of intra-domain protocols. OSPF, the most common intra-domain routing protocol used in the Internet today is based on single shortest path with equal splitting between next-hops of equal cost paths. Lorenz et al [40] show that OSPF routing performance could be improved by $O(N)$ if traffic-matrix aware explicit source-based multipath routing is used (e.g. MPLS-based [41], [42]).

Protocol extensions to support multipath routing (both in RIP and OSPF) have been studied by Narvaez et al [7], Chen et al [6] and Vutukury et al [8]. In [7], authors propose to find loop-free multipaths only by concatenating the shortest paths of their neighbors with their link to the neighbors. This approach essentially uses a depth first search with a depth of 1, whereas we allow arbitrary depth in our DFS-PU algorithm. Chen et al and Vutukury et al [6],

[8] propose more general multipath computations, but their schemes require the co-operation and upgrade of *all* the routers in the network. Chen et al present a general concept of suffix-matched path identifier to allow multipath computation using distributed computation, but they use *local labels* to realize the path like in ATM networks [21] or MPLS [22]. Therefore, they require a signaling protocol to map a global path specification to locally assigned labels at each node.

The proposed BANANAS framework allows source-based multipath routing using a "PathID". The use of a *globally significant path hash* allows multipath capabilities *without signaling* (i.e. in a connectionless manner) even in a *partially upgraded* network. The signaling requirement for source-routing is seen in protocols like ATM networks, MPLS networks [22] and NIMROD [12] routing (a link-state approach to inter-domain routing). IPv4 [19] and IPv6 [20], [13] provide a variable-length loose-source-routing option that may be considered "data-plane" signaling. But IPv4/v6 uses a uncompressed string of IP addresses in contrast to our efficient PathID encoding schemes.

MPLS has gained popularity in large ISPs, many ISPs prefer using OSPF/IS-IS to enable multipath and traffic engineering capabilities. This is due to the widespread deployment and operational experience available with OSPF/IS-IS. BANANAS extends the OSPF/IS-IS to allow such capabilities even in partially upgraded networks. The index-based scheme offers significant reduction of state complexity in comparison to MPLS label tables. The computation complexity incurred in BANANAS can also be further optimized using incremental k-shortest path algorithms similar to those suggested for OSPF's Dijkstra algorithm [43], [44].

In LIRA [11], Stoica et al briefly propose a forwarding scheme which they suggest could replace MPLS. A path is encoded as the XOR of router IDs along the path, and is processed along the path using a series of XOR operations. The work in LIRA is a special case of the BANANAS framework. In particular, the authors do not consider the larger architectural issues of partial upgrades, route-computation, state-computation tradeoffs, inter-domain operation etc. The focus in their paper was also different: a framework for service differentiation.

VII. Summary and Concluding Remarks

The key contributions in this paper can be summarized as follows.

a. Identification of abstract multipath architectural concepts (global PathID semantics, efficient path hashing) that are crucial to avoiding the need for signaling and allowing incremental network upgrades in connectionless routing protocols.

b. Canonical multipath and explicit path realizations in the context of legacy routing protocols: OSPF, BGP-4.

c. Demonstration of significant architectural flexibility: alternative PathID encodings, alternative route-computation algorithms (DFS-PU, k_i-shortest paths), movement of complexity to edges, division of functions between data-plane and control-plane, development of distributed validation algorithms etc.

d. Linux implementation results and integrated OSPF/BGP simulation results to validate various options

These building blocks can be used in two broad ways. First, in the context of traffic engineering within a partially upgraded legacy network. An operator may want to emulate signaled capabilities in a connectionless network (e.g.

see [42], [40]) or might desire fine-grained traffic management control hard to extract from parameter tweaking (e.g. see [31], [30], [32], [33]). The building blocks may be mixed and matched in a limited number of ways. For example, one could select a MD5+CRC32 encoding for BGP-4 (i.e. e-PathIDs) and a index-based encoding for OSPF (i-PathID). Obviously, a common encoding must be chosen across ISPs for the explicit AS-PATH case.

Second, and perhaps more important, the BANANAS framework building blocks could form the long-term basis for a best-effort end-to-end path multiplicity model. Through the independent partial upgrades of nodes in different autonomous systems, end-systems can have a growing *expectation* of multiple end-to-end paths. We strongly believe that such a mere *expectation* of end-to-end path multiplicity will trigger substantial application innovation.

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