Source-specific routing

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***Abstract*—Source-specific routing (not to be confused with source routing) is a routing technique where routing decisions depend on both the source and the destination address of a packet. Source-specific routing solves some difficult problems related to multihoming, notably in edge networks, and is therefore a useful addition to the multihoming toolbox. In this paper, we describe the semantics of source-specific packet forwarding, and describe the design and implementation of a source-specific extension to the Babel routing protocol as well as its implementation — to our knowledge, the first complete implementation of a source-specific dynamic routing protocol —, including a disambiguation algorithm that makes our implementation work over widely available networking APIs. We further discuss interoperability between ordinary next-hop and source-specific dynamic routing protocols. Our implementation has seen a moderate amount of deployment, notably as a testbed for the IETF Homenet working group.**

I. Introduction

The routing paradigm deployed on the Internet is next-hop routing. In next-hop routing, per-packet forwarding decisions are performed by examining a packet's destination address only, and mapping it to a next-hop router. Next-hop routing is a simple, well understood paradigm that works satisfactorily in a large number of cases.

The use of next-hop routing restricts the flexibility of the routing system in two ways. First, since a router only controls the next hop, a route $A \cdot B \cdot C \cdots Z$ can only be selected by the router A if its suffix $B \cdot C \cdots Z$ has already been selected by a neighbouring router B, which makes some forms of optimisation difficult or impossible. Other routing paradigms, such as circuit switching, label switching and source routing, do not have this limitation. (Source routing, in particular, has been proposed multiple times as a suitable routing paradigm for the Internet [11], but has been discouraged due to claimed security reasons [1]).

Second, the only decision criterion used by a router is the destination address: two packets with the same destination are always routed in the same manner. Yet, there are other data in the IP header that can reasonably be used for making a routing decision — the TOS octet, the IPv6 flow-id, and, of course, the source address.

We call *source-specific* routing the modest extension of classical next-hop routing where the forwarding decision is allowed to take into account the source of a packet in addition to its destination. Source-specific routing gives a modest amount of control over routing to the sending host, which can choose among different routes by picking different source addresses. The higher layers (transport or application) are therefore able to choose a route using standard networking APIs (collecting the host's local addresses and binding a socket to a specific address). Unlike source routing, however, source-specific routing remains a hop-by-hop mechanism, and therefore leaves local forwarding decisions firmly in the control of the routers.

Two things are needed in order to make source-specific routing practical: a forwarding mechanism that can discriminate on both source and destination addresses, and a dynamic routing protocol that is able to distribute source-specific routes. In this paper, we describe our experiences with the design and implementation of a source-specific extension to the Babel routing protocol [6], including a *disambiguation algorithm* that allows implementing source-specific routing over existing forwarding mechanisms.

ISBN 978-3-901882-68-5 © 2015 IFIP

II. Applications

The main application of source-specific routing is the implementation of *multihoming*.

A. Classical multihoming

A multihomed network is one that is connected to the Internet through two or more physical links. This is usually done in order to improve a network's fault tolerance, but can also be done in order to improve throughput or reduce cost.

Classically, multihoming is performed by assigning *Provider-Independent* addresses to the multihomed network and announcing them globally (in the *Default-Free Zone* (DFZ)) over the routing protocol. The dynamic nature of the routing protocol automatically provides for fault-tolerance; improvements in throughput and reductions in cost can be achieved by careful engineering of the routing protocol.

While classical multihoming works reasonably well in the network core, it does not apply to the edge. In order to perform classical multihoming, a network needs to be allocated a "Provider-Independent" prefix that is reannounced by some or all of a network's peers. This setup is usually impossible to achieve for home and small business networks.

Note that it is not in general possible to implement classical multihoming using a single "Provider-Dependent" prefix. If a network is connected to two providers A and B, a packet with a source address in an address range allocated to A will usually not be accepted by B, which will treat it as a packet with a spoofed source address and discard it [8]. What is more, A's prefix will not be reannounced by B, and hence destinations in A's prefix will not be reachable over the link to B.

There is some concern that classical multihoming, even when restricted to the large networks of the core, is causing uncontrolled growth of the "default-free routing table". Since we have only experimented with source-specific routing in edge networks, we hold no opinion on the usefulness of our techniques in the network core, and in particular on the desirability of adding it to the BGP external routing protocol.

B. Multihoming with multiple source addresses

Since announcing the same Provider-Dependent (PD) prefix to multiple ISPs is not always possible, it is a natural proposition to announce multiple PD prefixes, one per provider. In this approach, every host is assigned multiple addresses, one per provider, and extra mechanisms are needed (i) to choose a suitable source and destination address for each packet, and (ii) to properly route each outgoing packet according to both its source and its destination. In a sense, using multiple addresses splits the difficult problem of multihoming into two simpler problems that are handled at different layers of the network stack.

1) Choosing addresses: The choice of source and destination addresses is typically left to the application layer. All destination addresses are stored within the DNS (or explicitly carried by the application protocol), and the sending host tries them all, either in turn [7] or in parallel [12]; similarly, all possible source addresses are tried in turn. Once a flow is established, it is no longer possible to change the source and destination addresses — from the user's point of view, all TCP connections are broken whenever a link outage forces a change of address. Address selection can be implemented in the operating system's kernel and libraries, or by the application itself, which is notably done by most modern web browsers.

A different approach is to use a transport layer that has built-in support for multiple addresses and for dynamically renegotiating the set of source and destination addresses. One such transport layer is MPTCP [10]; we describe our experience with MPTCP in Section VII-B.

2) Source-specific routing: As mentioned above, a provider will discard packets with a source address that is in a different provider's prefix. In a network that is connected to multiple providers, each outgoing packet must therefore be routed through the link corresponding to its source address.

When the outgoing links are all connected to a single router, it is feasible to set up traffic engineering rules to ensure that this happens. There can be good reasons, however, why it is desirable to connect each provider to a different router (Figure 1): avoiding a single point of failure, load balancing, or simply that the various links use different link technologies that are not available in a single piece of hardware. In a home networking environment, the edge routers might be provided by the different service providers, with no possibility to consolidate their functionality in a single device.

With multiple edge routers, it is necessary that the routing protocol itself be able to route according to source addresses. We say that a routing protocol performs *source-specific* routing when it is able to take both source and destination addresses into account in its routing decisions.

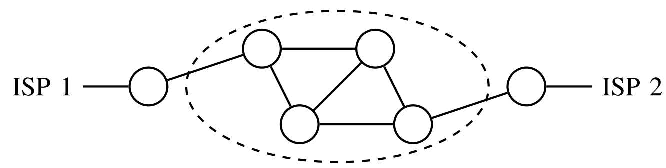


Fig. 1. A network connected to two providers

C. Other applications

In addition to multihoming with multiple addresses, we are aware of two problematic networking problems that source-specific routing solves cleanly and elegantly.

1) Overlay networks: Tunnels and VPNs are commonly used to establish a network-layer topology that is different from the physical topology, notably for security reasons. In many tunnel or VPN deployments, the end network uses its native default route, and only routes some set of prefixes through the tunnel or VPN.

In some deployments, however, the default route points at the tunnel. If this is done naively, the network stack attempts to route the encapsulated packets through the tunnel itself, which causes the tunnel to break. Many workarounds are possible, the simplest being to point a host route towards the tunnel endpoint through the native interface.

Source-specific routing provides a clean solution to that problem. The native default route is kept unchanged, while a source-specific default route is installed through the tunnel. The source-specific route being more specific than the native default route, packets from the user network are routed through the tunnel, while the encapsulated packets sourced at the edge router follow the native, non-specific route.

2) Controlled anycast: Anycast is a technique by which a single destination address is used to represent multiple network endpoints. A packet destined to an anycast address is routed to whichever endpoint is nearest to the source according to the routing protocol's metric. Anycast is useful for load balancing — for example, the DNS root servers are each multiple physical servers, represented by a single anycast address.

For most applications of anycast, all of the endpoints are equivalent and it does not matter which endpoint is accessed by a given client. Some applications, however, require that a given user population access a well-defined endpoint — for example, in a Content Distribution Network (CDN), a provider might not want to serve nodes that are not its customers. Ensuring that this is the case by tweaking the routing protocol's metric (or "prepending" in BGP parlance) is fragile and error-prone.

Source-specific routing provides an elegant solution to this problem. With source-specific routing, each instance of the distributed server is announced using a source-specific route, and will therefore only receive packets from a given network prefix.

III. Related work

Multihoming is a difficult problem, and, unsurprisingly, there are many techniques available to implement it, none of which are fully general. In addition to classical network-layer multihoming, already mentioned above, there are a number of lower-layer techniques, the use of which is usually completely transparent to the network layer; we are aware of *Multi-Link PPP*, of *Ethernet link aggregation (port trunking)*, of the use of MPLS to provide multiple paths across a rich link layer, as well as of proprietary techniques used by vendors of cable modems. Since these techniques work at the link layer, they are usually restricted to multihoming with a single provider.

All of these techniques are compatible, in the sense that they can be used at the same time. We imagine a home network where source-specific routing is used to access two providers, each of which is classically multihomed, over links that consist of multiple physical links combined at the link layer.

Source-specific packet forwarding itself is not a new idea [3], and implementing it manually on a single router using traffic engineering interfaces is a well-documented technique [9]. Implementing source-specific routing within the routing protocol has been proposed by Bagnulo et al. [2], but the techniques used differ significantly from ours. First, the authors only deal with the non-overlapping case — where the different possible sources are disjoint —, which avoids the need for the disambiguation algorithm which is one of our main concerns. Second, they use a more general facility of an existing routing protocol (BGP Communities) rather than explicitly implementing source-specific routing. We find our more direct approach to be more intuitive, and expect it to be more reliable, since it doesn't require out-of-band agreement on the meaning of the labels carried by the routing protocol.

More generally, there are other applications of routing based on more information from the packet header than just the destination address. The traffic-engineering community has been experimenting with routing based on the TOS octet of the IPv4 header for many years, and the ability to do that is part of the OSPFv2 protocol. TOS-based routing is somewhat analoguous to source-specific routing, and many of the issues raised are similar; both can be seen as particular cases of "multi-dimensional routing".

Equal Cost Multipath (ECMP) is somewhat different. A router performing ECMP has multiple routes to the same destination, and chooses among them according to the value of a hash of the packet header. While ECMP does route on multiple header fields, the choice of fields used to choose a route in ECMP is a purely local matter, and does not need to be carried by the routing protocol.

IV. Source-specific routing

A. Next-hop routing tables

Ordinary next-hop routing consists in mapping a destination address to a next-hop. Obviously, it is not practical to maintain a mapping for each possible destination address, so the mapping table must be compressed in some manner. The standard compressed data structure is the *routing table* (or *Forwarding Information Base*, FIB), which ranges over *prefixes*, ranges of addresses the size of which is a power of two. The routing table can be constructed manually, but is usually populated by a routing protocol.

Since prefixes can overlap, the routing table is an ambiguous data structure: a packet's destination address can match multiple routing entries. This ambiguity is resolved by the so-called *longest-prefix rule*: when multiple routing table entries match a given destination address, the most specific matching entry is the one that is used.

More precisely, a prefix is a pair $P = p/plen$, where p is the first address in the prefix and $plen$ is the *prefix length*. An address a is in P when the first $plen$ bits of a match the first $plen$ bits of p. We say that a prefix $P = p/plen$ is more specific than a prefix $P' = p'/plen'$, written $P \leq P'$, when the set of addresses in P is included in the set of addresses in P'. Clearly, $P \leq P'$ if and only if $plen \geq plen'$, and the first $plen'$ bits of p and p' match.

The specificity ordering defined above has an important property: given two prefixes P and P', they are either disjoint ($P \cap P' = \emptyset$), or one is more specific than the other ($P \leq P'$ or $P' \leq P$).

A routing table is a set of pairs (P, nh), where P is a prefix and nh, the *next hop*, is a pair of an interface and a (link-local) address; we further require that all the prefixes in a routing table be distinct. Because of the particular structure of prefixes, given an address a, either the set of prefixes in the routing table containing a is empty, or it is a chain (a totally ordered set); hence, there exists a most specific prefix P in the routing table containing a. The longest-prefix rule specifies that the next hop chosen for routing a packet with destination a is the one corresponding to this most specific prefix, if any.

B. Source-specific routing tables

Source-specific routing is an extension to next-hop routing where both the destination and the source of a packet can be used to perform a routing decision. Source-specific routers use a *source-specific* routing table, which is a set of triples (d, s, nh), where d is a destination prefix, s a source prefix, and nh is a next hop (note the ordering — destination comes first). Such an entry matches a packet with destination address a_d and source address a_s if a_d is in d and a_s is in s. The specificity ordering generalises easily to pairs: a pair of prefixes (d, s) is more specific than a pair (d', s') when all pairs of addresses (a_d, a_s) which are in (d, s) are also in (d', s'); clearly, $(d, s) \leq (d', s')$ when $d \leq d'$ and $s \leq s'$.

Unfortunately, the set of destination-source pairs of prefixes equipped with the specificity ordering does not have the same structure as the set of single prefixes: given a pair of addresses (a_d, a_s), the set of pairs of prefixes containing (a_d, a_s) might not be a chain. Consider the pairs $(\text{2001:db8:1::/48}, \text{::/0})$ and $(\text{::/0}, \text{2001:db8:2::/48})$. Clearly, these two pairs are not disjoint (the pair of addresses $(\text{2001:db8:1::1}, \text{2001:db8:2::1})$ is matched by both), but neither is one more specific than the other — the pair $(\text{2001:db8:1::1}, \text{2001:db8:3::1})$ is matched by the first but not the second, and, symmetrically, the pair $(\text{2001:db8:4::1}, \text{2001:db8:2::1})$ is matched by just the second.

From a practical point of view, this means that a source-specific routing table can contain multiple most-specific entries, and thus fail to unambiguously specify a forwarding behaviour.

We say that a source-specific routing table is *ambiguous* when it contains multiple non-disjoint most-specific entries. Two entries r_1 and r_2 that are neither disjoint nor ordered are said to be *conflicting*, written $r_1 \# r_2$. If $r_1 = (d_1, s_1)$ and $r_2 = (d_2, s_2)$, then this is equivalent to saying that either $d_1 < d_2$ and $s_1 > s_2$ or $d_1 > d_2$ and $s_1 < s_2$. We call the *conflict zone* of r_1 and r_2 the set of (a_d, a_s) that are matched by both r_1 and r_2.

C. Forwarding behaviour

In the presence of an ambiguous routing table, there exist packets that are matched by distinct most-specific entries. An arbitrary choice must be made in order to decide how to route such a packet.

Let us first remark that all routers in a single routing domain must make a consistent choice — having different routers follow different policies within conflict zones may lead to persistent routing loops. Consider the topology in Figure 2, with two source-specific routes indexed by the pairs (d_1, s_1) and (d_2, s_2) respectively, where packets matching (d_1, s_1) are sent towards the left of the diagram, and packets matching (d_2, s_2) are sent towards the right. If the two pairs are in conflict, and router A chooses (d_2, s_2) while B chooses (d_1, s_1), then a packet matching both pairs will loop between A and B indefinitely.

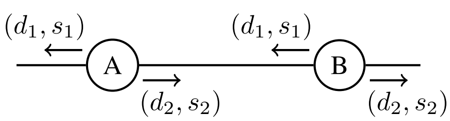


Fig. 2. A routing loop due to incoherent orderings

It is therefore necessary to choose a disambiguation rule that is uniform across the routing domain. There are two natural choices: discriminating on the destination first, and comparing sources if destinations are equal, or discriminating on source first. More precisely, the destination-first ordering is defined by:

$$(d, s) \preceq (d', s') \text{ if } d < d' \text{ or } d = d' \text{ and } s \leq s',$$

while the source-first ordering is defined by

$$(d, s) \preceq_s (d', s') \text{ if } s < s' \text{ or } s = s' \text{ and } d \leq d'.$$

These orderings are isomorphic — hence, there is no theoretical argument that allows us to choose between them. An engineering choice must be made, based on usefulness alone.

The current consensus, both within the IETF Homenet group and outside it, appears to be that the destination-first ordering is the more useful of the two. Consider the (fairly realistic) topology in Figure 3, where an edge router A announces a source-specific route towards the Internet, and a stub network N announces a (non-specific) route to itself. A packet matching both routes must follow the route towards N, since it is obviously the only route that can reach the destination, which implies that A must use the destination-first ordering. On the other hand, we know of no such compelling examples of the usefulness of the source-first ordering.

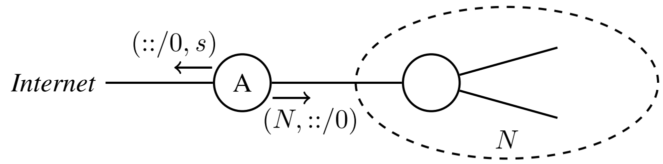


Fig. 3. A stub network behind a source-specific router

In the following sections, we describe our experience with source-specific routing using the destination-first ordering. However, nothing in this article depends on the particular ordering being used, and our techniques would apply just as well to any structure that is a refinement of the specificity ordering and that is totally ordered on route entries containing a given address.

V. Implementing source-specific routing

In the previous sections, we have described source-specific routing and shown how all routers in a routing domain must make the same choices with respect to ambiguous routing tables, and have argued in favour of the destination-first semantics. Whichever particular choice is made by an implementation of a routing protocol, however, must be implementable in terms of the primitives made available by the lower layers (the operating system kernel and the hardware).

In this section, we describe the two techniques that we have used to implement a source-specific extension to the Babel routing protocol [4]. We first describe the technique that we use when running over a lower layer that natively implements destination-first source-specific routing (Section V-A). We then describe our so-called "disambiguation" algorithm (Section V-B) which we use to implement destination-first source-specific routing over any source-specific facility provided by the lower layers, as long as it is compatible with the specificity ordering — a very mild hypothesis that is satisfied by a number of widely available implementations.

A. Native source-specific FIB

Ideally, we would like the lower layers of the system (the OS kernel, the line cards, etc.) to implement destination-first source-specific routing tables out of the box. Such native support for source-specific routing is preferable to the algorithm described below, since no additional routes will need to be installed. In practice, while many systems have a facility for source-specific traffic engineering, this lower-layer support often has a behaviour different from the one that we require.

The Linux kernel, when compiled with the relevant options ("ipv6-subtrees"), supports source-specific FIBs natively, albeit for IPv6 only. Unfortunately, this support is only functional since Linux 3.11 (source-specific routes were treated as unreachable in earlier versions), and only for IPv6 (for IPv4, the "source" datum is silently ignored). We know of no other TCP/IP stacks with native support for destination-first source-specific routing — other techniques must be used on most systems.

B. Disambiguation of a routing table

All versions of Linux, some versions of FreeBSD, and a number of other networking stacks implement a facility to manipulate multiple routing tables and to select a particular one depending on the source address of a packet. Since the table is selected before the destination address is examined, these API implement the source-first behaviour, which is not what we aim to implement.

In this section, we describe a disambiguation algorithm that can be used to maintain a routing table that is free of ambiguities, and will therefore yield the same behaviour as long as the underlying forwarding mechanism implements a behaviour that is compatible with the specificity ordering (Section IV-B). All the forwarding mechanisms known to us satisfy this very mild hypothesis.

Recall that a routing table is ambiguous if there exists a packet that is matched by at least one entry in the table and such that there is no most-specific entry among the matching entries. A necessary and sufficient property for a routing table to be non-ambiguous is that every conflict zone is equal to the union of more specific route entries.

The algorithm that we propose maintains, for each conflict, exactly one route entry that covers exactly the conflict zone. While a more parsimonious solution would be possible in some cases, it would greatly complicate the algorithm.

a) Weak completeness: We say that a routing table is *weakly complete* if each conflict zone is covered by more specific entries. More formally, T is weakly complete if $\forall r_1, r_2 \in T, r_1 \cap r_2 = \bigcup\{r \in T \mid r \leq r_1 \cap r_2\}$.

Theorem 1. *A routing table is non-ambiguous if and only if it is weakly complete.*

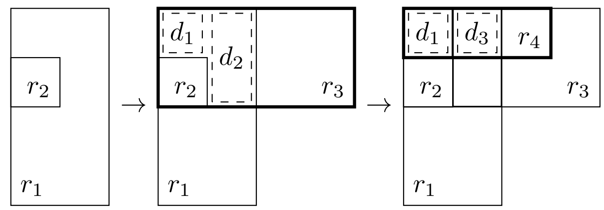
Proof: Let $U_x^y = \bigcup\{r \in T \,|\, r \leq x \cap y\}$. We need to show that T is non-ambiguous iff $\forall r_1, r_2 \in T, r_1 \cap r_2 = U_{r_1}^{r_2}$.

($\Leftarrow$) Suppose T is weakly complete, and consider two route entries $x, y \in T$ in conflict. By weak completeness, $U_x^y = x \cap y$, so for all addresses $a \in x \cap y$, there exists a route $r \in U_x^y$ such that $a \in U_x^y$. Since $r \in x \cap y$, we have $r < x$ and $r < y$, and r is more specific than $x \cap y$. Since this is true for all conflicts, the table is not ambiguous.

($\Rightarrow$) Suppose T is non-ambiguous and not weakly complete. Then there exist two entries $x, y \in T$ in conflict such that $x \cap y \neq U_x^y$. Consider an address $a \in x \cap y \setminus U_x^y$, and an entry $r \in T$ matching a. Clearly, $r \supsetneq x \cap y$, and so either $r \# x$ or $r \# y$, or $r > x$ and $r > y$. In all cases, r is not more specific than both x and y, so there is no minimum for the set of entries matching a. This contradicts the hypothesis, so if T is not ambiguous, it is weakly complete. ∎

Disambiguation with weak completeness is not convenient, since it may require adding multiple route entries to solve a single conflict, and the disambiguation routes added may generate additional conflicts. Suppose for example that the FIB first contains two entries $r_1 > r_2$, and we add $r_3 > r_2$ which conflicts with r_1 (see figure below). Since $r_2 < r_3$, there is no conflict within r_2, but we need disambiguation routes d_1 and d_2. The FIB is now weakly complete.

Suppose now that we add $r_4 < r_3$ in conflict both with r_1 and the disambiguation route d_2. We install a new disambiguation entry d_3. Note also that since $r_4 < r_3$, we need to use the next-hop of r_4 for the former region covered by d_1: we need to change the currently installed disambiguation route entry.



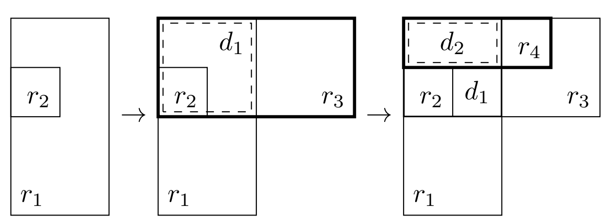
Some of this complexity can be avoided by requiring a stronger notion of completeness.

b) Completeness: A routing table is *(strongly) complete* if each conflict zone is covered by one route entry. More formally, T is complete if $\forall r_1, r_2 \in T, r_1 \cap r_2 \in T$. This obviously implies weak-completeness, and therefore a complete routing table is not ambiguous. Our algorithm maintains the completeness of the routing table.

Theorem 2. *Adding routes to achieve completeness does not lead to* another *conflict.*

Proof: Suppose that $r_1 = (d_1, s_1)$ and $r_2 = (d_2, s_2)$ are two route entries in conflict, where $d_1 < d_2$ and $s_1 > s_2$. Consider the disambiguation entry $r_{sol} = (d_1, s_2)$ which disambiguates this conflict. Suppose now that r_{sol} is in conflict with another route entry $r_3 = (d_3, s_3)$. We have either $d_1 < d_3$ and $s_1 > s_2 > s_3$, in which case $r_3 \# r_1$; or $d_2 > d_1 > d_3$ and $s_2 < s_3$, in which case $r_3 \# r_2$. In either case, the conflict existed beforehand, and must therefore already have been resolved. ∎

Take the previous example again. When adding r_3, we add one route entry to cover the area d_1 ($r_1 \cap r_3$). Since r_2 is more specific, the new route entry does not affect the routing decision for addresses in r_2. When adding r_4, it is in conflict with both r_1 and the disambiguation route d_1, but for the same conflict zone $r_4 \cap r_1$. The disambiguation route inserted is thus not an additional conflict.



c) Preliminaries: We write $\min(r_1, r_2)$ for the minimum according to $\preceq$. We define two auxiliary functions. The function $\text{min\_conflict}(zone, r)$ (Algorithm 1) returns, if it exists, the minimum route entry in conflict with r for the conflict zone $zone$. The function $\text{conflict\_solution}(zone)$ (Algorithm 2) returns, if it exists, the minimum route entry participating in a conflict for the zone $zone$.

```
Function min_conflict(zone, r)
    min ← ⊥
    for all r1 ∈ T
    s.t. r # r1 and r ∩ r1 = zone
        min ← min(r1, min)
    return min
```

Algorithm 1: search for mininum conflicting route

```
Function conflict_solution(zone)
    min ← ⊥
    for all r1, r2 ∈ T
    s.t. r1 # r2 and r1 ∩ r2 = zone and r1 ≺ r2
        min ← min(r1, min)
    return min
```

Algorithm 2: Search for conflict solution

We write $\text{nh}(r)$ for the next hop of a route r.

We use three primitives for manipulating the routing table. Let $r = (d, s, nh)$ be a route entry, and nh' a nex-thop. Then $\text{install}(r, nh')$ adds the route entry (d, s, nh'), $\text{uninstall}(r, nh')$ removes the route entry (d, s, nh'), and $\text{switch}(r, nh', nh'')$ changes the FIB's route entry (d, s, nh') to (d, s, nh''). Calling $\text{switch}(r, nh', nh'')$ is equivalent to calling $\text{uninstall}(r, nh')$ followed by $\text{install}(r, nh'')$.

d) Relevant conflicts: Consider a route entry r, and a set E of routing entries in conflict with r for the same conflict zone; all of these conflicts will have the same resolution. Moreover, if the resolution was caused by a route in E, then that was necessarily the more specific of the entries in E. Note that the minimum exists because elements of E have either the same destination, or the same source, and match at least one address in r.

Given a route entry r, we define the equivalence $\sim_r$ by $r_1 \sim_r r_2 \Leftrightarrow r_1 \cap r = r_2 \cap r$, i.e. two route entries are equivalent for $\sim_r$ if they have the same intersection with r. If two equivalent route entries are in conflict with r, this means that they have the same conflict zone.

Quotienting a set of routing entries in conflict with r by this equivalence, and taking the minimum of each of the class of equivalence gives us exactly the routes that we care about.

e) Adding a route entry (Algorithm 3): Installing a new route entry in the FIB may make it ambiguous. For this reason, we must install the most specific routing entries first. In particular, we must install disambiguation entries (lines 2 to 9) before the route itself (lines 10 to 14).

Let r be the route to install, and C the set of route entries in conflict with r, for which there is no natural solution, i.e. $C = \{r' \in T \mid r' \# r \text{ and } r' \cap r \notin T\}$ (line 3). We only consider the relevant conflicts upon this set (line 4): $C' = \{\min(E) \mid E \in C/_{\sim_r}\}$.

For each route entry $r_1 \in C'$ (considering the most specific first), we first search (line 5), if it exists, the minimum route entry r_2 such that $r_2 \# r_1$ and $r_2 \cap r_1 = r \cap r_1$. If r_2 does not exist, then there was no conflict for this zone before, and we must add $((r_1 \cap r), nh)$ to the FIB (line 7). Otherwise, a routing entry has been installed for this conflict, and we must decide if the new route entry r is or not the new candidate, which is true if it is more desirable ($\preceq$) than both r_2 and r_1 (line 8). If it is the case, then the previous next-hop installed was the one of r_2: we replace $((r_1 \cap r), nh_2)$ by $((r_1 \cap r), nh)$ (line 9).

Finally, we must search if there exists two route entries in conflict for the zone of r (line 10). In that case, a disambiguation route entry has been installed, so r must replace it (line 12). Otherwise, r can be added normally (line 14). We end the procedure by adding r to our local RIB (line 15).

```
1  Function add_route(r)
2      for all r1 ∈ T
3      s.t. r # r1 and r ∩ r1 ∉ T
4      and r1 = min_conflict(r ∩ r1, r)
5          r2 ← min_conflict(r ∩ r1, r1)
6          if r2 = ⊥
7              install(r ∩ r1, nh(min(r, r1)))
8          else if r ≺ r2 and r ≺ r1
9              switch(r ∩ r1, nh(r2), nh(r))
10     r1 ← conflict_solution(r)
11     if r1 = ⊥
12         install(r, nh(r))
13     else
14         switch(r, nh(r1), nh(r))
15     T ← T ∪ {r}
```

Algorithm 3: Route addition

f) Removing a route entry (Algorithm 4): This time, we must first remove the less specific route first to keep the routing table unambiguous. Again, we write r for the route to be removed. First, remove r from the RIB (line 2). As for the addition, r may be solving a conflict, in which case we cannot just remove it, but must first search for the entry covering that conflict (line 3), and if it exists replace r's next-hop (line 7). Otherwise, we just remove r from the FIB (line 5).

We consider C' as previously defined (lines 9 and 10). For each route entry $r_1 \in C'$ (considering the less specific first), we first search, as we did for the adding process, for the minimum route entry r_2 such that $r_2 \# r_1$ and $r_2 \cap r_1 = r \cap r_1$ (line 11). If r_2 does not exist, we remove $((r_1 \cap r), nh)$ from the FIB (line 13). Otherwise, for the same reasons above, if r is more desirable than both r_1 and r_2, then we replace in the FIB the next-hop of r assigned for $r \cap r_1$ by the one of r_2 (line 15).

Function delete_route(r)
$T \leftarrow T \setminus \{r\}$
$r_1 \leftarrow$ conflict_solution(r)
if $r_1 = \bot$
uninstall($r, \mathrm{nh}(r)$)
else
switch($r, \mathrm{nh}(r), \mathrm{nh}(r_1)$)
for all $r_1 \in T$
s.t. $r \# r_1$ *and* $r \cap r_1 \notin T$
and $r_1 = \mathrm{min\_conflict}(r \cap r_1, r)$
$r_2 \leftarrow \mathrm{min\_conflict}(r \cap r_1, r_1)$
if $r_2 = \bot$
uninstall($r \cap r_1, \mathrm{nh}(\min(r, r_1))$)
else if $r \prec r_2$ *and* $r \prec r_1$
switch($r \cap r_1, \mathrm{nh}(r), \mathrm{nh}(r_2)$)

Algorithm 4: Route deletion

g) Changing a route entry (Algorithm 5): This is the simplest case, since disambiguation routes must be maintained, and changed only if the route that we want to change has been selected for disambiguation. The order in which we change the route entries does not matter. Let r the route entry to change by r_{new}. Here, we choose to first replace r by r_{new} (line 2).

We consider C' as previously defined (lines 3 and 4). For each route entry $r_1 \in C'$, we search for the minimum route entry r_2 such that $r_2 \# r_1$ and $r_2 \cap r_1 = r \cap r_1$. If both $r \prec r_1$ and r_2 is r (line 6), then we replace the next-hop nh of the corresponding disambiguation route entry by the new one nh_{new} (line 7).

1 **Function** change_route(r, r_{new})
2 switch($r, \mathrm{nh}(r), \mathrm{nh}(r_{new})$)
3 **for all** $r_1 \in T$
4 *s.t.* $r \# r_1$ *and* $r \cap r_1 \notin T$
5 *and* $r_1 = \mathrm{min\_conflict}(r \cap r_1, r)$
6 *and* $r \prec r_1$ *and* $r = \mathrm{min\_conflict}(r \cap r_1, r_1)$
7 switch($r \cap r_1, \mathrm{nh}(r), \mathrm{nh}(r_{new})$)

Algorithm 5: Route modification

C. External changes to the routing table

In the description above, we have asssumed that only our algorithm ever needs to manipulate the routing table. In practice, however, the routing table is also manipulated by other agents — other routing protocols or human operators. In principle, the same algorithm should be applied to externally changed routes; however, this is not implemented yet.

VI. Source-specific Bellman-Ford

The distributed Bellman-Ford algorithm is the foundation of a number of more or less widely deployed routing protocols, such as the venerable RIP, EIGRP, Babel and, arguably, BGP. In order to experiment with source-specific routing, we have implemented a source-specific variant of the Babel routing protocol [6]; the exact details of the packet format of our extension are described in [4]. Our implementation has seen a moderate amount of deployment, most notably as a testbed for the IETF Homenet working group [5].

Ordinary (next-hop) distributed Bellman-Ford maintains a *routing table* which associates, to each known destination prefix, a next-hop router and a metric; each prefix and metric pair is advertised to neighbours in periodic *update* messages. In source-specific Bellman-Ford, the routing table is indexed by pairs of a destination prefix and a source prefix, and (source-specific) updates advertise a triple of a destination prefix, a source prefix, and a metric.

The source-specific extension to Babel adds a new kind of source-specific update message in addition to the original, non-specific update. Since Babel's loop-avoidance mechanism relies on two kinds of request messages, it also adds two new kinds of source-specific requests. All of these are encoded as new kinds of messages rather than extensions to existing messages, which causes them to be silently ignored by unextended Babel routers, and ensures that our extension interoperates with the original Babel protocol.

A. Bootstrapping

In distributed Bellman-Ford, a prefix is reannounced after it has been learnt from a neighbour. This process is bootstrapped by announcing prefixes learned from a different source (typically a different routing protocol or a static route); in Babel, this is known as *redistribution*.

Just like ordinary routes, source-specific routes are originated by performing redistribution. In case a source-specific route is already present, our implementation is able to redistribute it; more generally, the filtering language allows attaching a source prefix to a non-specific route at redistribution time. While careless use of this facility may cause persistent routing loops to occur, this is expected with careless redistribution.

B. Interoperability

The Babel protocol has seen a moderate amount of deployment in production networks, and is usually deployed within cheap routers that can be difficult to update with a source-specific version of the protocol. We have therefore paid particular attention to the issue of interoperability between routers running the source-specific and unextended protocols.

The extended version of the protocol uses both non-specific and specific update messages. In principle, a non-specific route could be announced in two manners: by using a non-specific update carrying the destination prefix d, or by using a source-specific update carrying the pair $(d, ::/0)$. As we want non-specific routes to be propagated between source-specific and non-specific routers, source-specific routers interpret a non-specific update as a source-specific update with a source prefix of $::/0$, and, conversely, source-specific routers never send source-specific updates of the form $(d, ::/0)$, preferring the non-specific form instead.

A more difficult issue is how a non-specific router should interpret a source-specific update. There are two possibilities: the source can be discarded and the update treated as non-specific, or the entire update can be discarded. The first of these possibilities can cause persistent routing loops.

Consider two nodes A and B, with A source-specific announcing a route to (d, s) (Figure 4). Suppose that B ignores the source information when it receives the update, and reannounces it as d. This is reannounced to A, which treats it as $(d, ::/0)$. Packets destined to d but not sourced in s will be forwarded by A to B, and by B to A, causing a persistent routing loop.

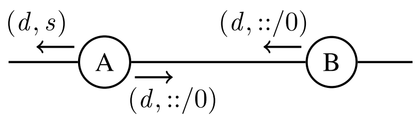


Fig. 4. Non-specific routers cannot accept specific routes

On the other hand, if non-source-specific nodes reject source-specific updates, but source-specific nodes accept non-specific updates, then source-specific nodes can communicate entries of the form $(d, ::/0)$ and are completely compatible with non-source-specific nodes. In this case, Bellman-Ford will eventually converge to a loop-free configuration.

In general, discarding of source-specific routes by non-specific routers will cause routing blackholes. Intuitively, unless there are enough non-specific routes in the network, non-specific routers will suffer starvation, and discard packets for destinations that are only announced by source-specific routers. A simple yet sufficient condition for avoiding black-holes is to build a connected source-specific backbone that includes all of the edge routers, and announce a (non-specific) default route towards the backbone.

VII. Experimental results

We have implemented both schemes described in Sections V-A and V-B within `babeld`, a Linux implementation of the Babel routing protocol. This has allowed us to perform a number of experiments which we describe in this section.

Our experimental network consists of a mesh network consisting of a dozen OpenWRT routers and a single server running Debian Linux. Two of the mesh routers have a wired connection to the Internet, and are connected to the server through VPNs (over IPv4). All of the routers run our modified version of the Babel protocol.

IPv4 connectivity for the mesh is provided by the Debian server, which acts as a NAT box. The IPv6 connectivity is more interesting: there are two IPv6 prefixes, one of which is a native prefix provided by our employer's network, the other one being routed through the VPN. The network therefore has two source-specific default IPv6 routes.

A. Routing table for VPN connectivity

Figure 5 shows an excerpt of the routing tables of one of the two wired routers. The modified `babeld` daemon has allocated a non-default routing table, table 11, and inserted routes (marked as `proto 42`) into both the default `main` table and table 11. The former contains non-specific routes: the default route and the `/20` subnet announced by our local DHCP server, and host routes to individual mesh nodes. The encapsulated VPN packets are routed through the default route.

```
# ip rule show
0: from all lookup local
101: from 192.168.4.0/24 lookup 11
32766: from all lookup main
32767: from all lookup default
# ip route show
default via 172.23.47.254 dev eth1 proto static
172.23.32.0/20 dev eth1 proto kernel src 172.23.36.138
192.168.4.20 via 192.168.4.20 dev tun-ariane proto 42 onlink
192.168.4.30 via 192.168.4.30 dev wlan1 proto 42 onlink
[...]
# ip route show table 11
default via 192.168.4.20 dev tun-ariane proto 42 onlink
192.168.4.20 via 192.168.4.20 dev tun-ariane proto 42 onlink
192.168.4.30 via 192.168.4.30 dev wlan1 proto 42 onlink
[...]
```

Fig. 5. IPv4 routing table on a router using a VPN

Table 11 contains routes for locally originated packets, sourced in 192.168.4.0/24. The only "real" route in this table is the default route, which prevents the VPN from attempting to "enter itself". The other routes are disambiguation routes, automatically generated by the algorithm described in Section V-B. These entries are copies of those present in the main routing table, and prevent locally generated packets destined to local subnets from leaving through the native default route.

B. Multipath TCP

Multipath TCP [10] is an extension to TCP which multiplexes a single application-layer flow over multiple network layer sub-flows, and attempts to use as many distinct routes as possible, and to either carry traffic over the most efficient one or to perform load balancing. An obvious application is a mobile node (a telephone) with permanent connectivity to a cellular network and intermittent WiFi connectivity: MPTCP is able to use the cellular link when WiFi is not available, and switch to WiFi when available without dropping already established connections.

Multipath TCP and source-specific routing turn out to be a surprisingly good match. MPTCP is able to use all of the addresses of the local host, and to dynamically probe the reliability and performance of packets sourced from each.

We have performed two tests that both consist in downloading a 110 MB file over MPTCP from the MPTCP website. In the first test (Figure 6), a desktop computer is directly connected to the source-specifically routed wired network, and is configured with two IPv4 addresses. The Linux `tc` subsystem is used to limit each of the addresses to 100 kB/s traffic; MPTCP is able to reliably download at 200 kB/s.

In the second test (Figure 7), a laptop's WiFi interface is configured with three addresses (one IPv4 and two IPv6). MPTCP multiplexes the traffic across the three routes, and balances their throughput dynamically.

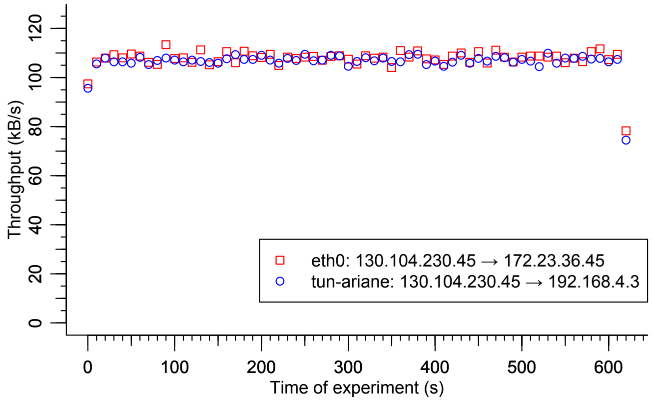


Fig. 6. Download using MPTCP and traffic control

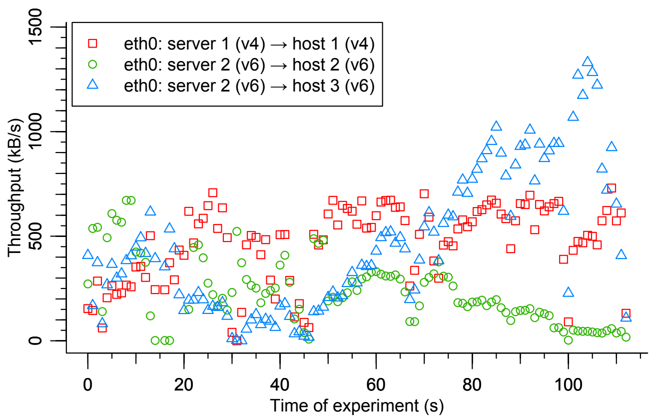


Fig. 7. Download using MPTCP

VIII. Conclusion and further work

Source-specific routing is a modest extension to next-hop routing that keeps the forwarding decisions firmly within control of the routers while allowing end hosts a moderate and clearly defined amount of control over the choice of routes. Since source-specific routing can cause ambiguous routing tables, we have defined the behaviour that we believe source-specific routers should have, and shown how combining different behaviours in the same network can cause persistent routing loops. Similar care must be taken when combining non-specific with source-specific routers in the same network. We have proposed two ways to implement source-specific routing, and obtained experimental results that show that source-specific routing can be usefully exploited by the transport layer protocol MPTCP. Our implementation is of production quality, and has seen a modest amount of deployment, notably as a testbed for the ideas of the IETF Homenet working group.

While we enjoy working with distance-vector protocols, much of the networking community appears to have converged on using the OSPF protocol for internal routing. OSPF is a rich and complex protocol, and while many of our techniques should apply without difficulty to it, actually implementing a full source-specific variant of OSPF without sacrificing any of its flexibility remains a challenging endeavour.

It was a pleasant surprise to discover that unmodified MPTCP can use source-specific routes without any manual configuration. However, we claim that source-specific routing can also be exploited at the application layer, and we are currently working on an extension to the *Mosh* [13] UDP-based remote shell that is able to dynamically balance over multiple source-specific routes.

Finally, we have only considered the applicability of source-specific routing to edge networks, which tend to carry only a moderate number of distinct routes. However, there is nothing in principle that would prevent source-specific routing from being applicable to BGP and to core networks, where it could perhaps be used for some forms of multihoming and traffic engineering without the routing table growth due to classical multihoming. Extending our results to core networks, with their large routing tables, will require careful analysis of the complexity of our techniques, and a carefully optimised implementation.

Code availability

The source-specific version of Babel is available from https://github.com/jech/babeld.

Acknowledgements

We are grateful to Benoît Valiron for his help with the presentation of the disambiguation algorithm.

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