Toward Compact Interdomain Routing

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Abstract

Despite prevailing concerns that the current Internet interdomain routing system will not scale to meet the needs of the 21st century global Internet, networking research has not yet led to the construction of a new routing architecture with satisfactory and mathematically provable scalability characteristics. Worse, continuing empirical trends of the existing routing and topology structure of the Internet are alarming: the foundational principles of the current routing and addressing architecture are an inherently bad match for the naturally evolving structure of Internet interdomain topology. We are fortunate that a sister discipline, theory of distributed computation, has developed routing algorithms that offer promising potential for genuinely scalable routing on realistic Internet-like topologies. Indeed, there are many recent breakthroughs in the area of compact routing, which has been shown to drastically outperform, in terms of efficiency and scalability, even the boldest proposals developed in networking research. Many open questions remain, but we believe the applicability of compact routing techniques to Internet interdomain routing is a research area whose potential payoff for the future of networking is too high to ignore.

1 Introduction

The relentless growth of the Internet has brought with it inevitable, and inextricable, economic and social dependence on this infrastructure. In reality, the dependence is mutual: without a robust source of economic support, the Internet will be unable to evolve toward the potential it quite imaginably holds. We believe that we will soon be faced with a critical architectural inflection point in the Internet. Most experts agree\(^1\) that the existing data network architecture is severely stressed and reaching its capability limits. The evolutionary dynamics of several critical components of the infrastructure suggest that the existing system will not scale properly to accommodate even another decade of growth. While ad hoc patches, some of them quite clever, have offered temporary relief, both the research and operational communities concur that a fundamental top-to-bottom reexamination of the routing architecture is requisite to a lasting solution.

In this paper we set to work on such reexamination. We clarify up front that we adhere to standard reductionism in this work: given a complex system—existing interdomain routing—that we want to fix, we seek to decompose it into constituents that we can tackle one-by-one, since each constituent problem has a chance of admitting formalization and rigorous solution. We can then construct the final solution—a future Internet routing architecture—from the solutions to subproblems. The constituent problem we will examine in this paper is routing scalability, though it is well-established that scalability is only one of many problems of the current Internet routing architecture.\(^2\)

More specifically, we analyze the fundamental causes of the global interdomain routing scalability problems, and how they imply the need for dramatically more efficient routing algorithms with rigorously proven worst-case performance guarantees. Fortunately, such algorithms exist—they are known collectively as compact routing. But before we review these techniques (Section 5), we first reduce Internet scalability problems to compact routing formalism. In Section 4 we will peel off the surface layers of the complexity of the current interdomain routing system to reveal the roots of its scalability inefficiencies. One of the serious practical concerns with compact routing is that it does not guarantee the use of shortest paths: it “stretches” them. We discuss the stretch of a routing algorithm in Section 3, and contrast it with more familiar forms of path-length inflation in today’s interdomain routing. This discussion naturally leads to our explanation of why hierarchical routing will not scale if deployed in the Internet (Section 4). After we survey the history of compact routing in Section 5 we analyze the key aspects of its applicability to Internet interdomain routing in Section 6. Such analysis yields an outline of future work in this area. We conclude in Section 7 with a vivifying summary.

2 Routing scalability

Poor scaling of a routing protocol expresses itself in terms of rapid (linear) rates of growth of the routing table (RT) size as well as convergence parameters (convergence time, churn, instabilities, etc.). In this paper we concentrate on the subproblem associated with the former component, but we also discuss the latter in Section 6.

The immediate causes of Internet RT growth have been extensively studied and analyzed\(^2\)\(^3\)\(^4\)\(^5\)\(^6\)\(^7\). Several studies, proposals, and even new routing architectures seek to directly address these causes. Prominent efforts in this area include\(^8\)\(^9\)\(^10\)\(^11\)\(^12\) and most recently\(^13\)\(^14\). However, we argue that even if we could manage to deploy any

\(^1\)See\(^ 1\)\(^2\)\(^3\)\(^4\)\(^5\) for few examples.

\(^2\)Other problems include security, isolation, configuration control, etc. See\(^ 1\) for a long list of future routing architecture requirements.
future

same way as the existing architecture is only postponing the problem. Although the difference in impact between alternatives to the existing architecture may be small today, in the long run a constant factor reduction is negligible compared to the performance gain from a genuinely scalable solution. Any solution that scales in essentially the same way as the existing architecture is only postponing the problem.

of the proposed approaches, it would represent only a short-term patch, because they address symptoms rather than the root of the problem. It is empirically clear that the Internet needs more than a short-term fix.

As an example, we consider the idea of routing on AS numbers, where AS numbers replace IP prefixes in the role of interdomain routing addresses. This idea is now a common part of many proposals [9, 11, 12, 13, 14]. At first glance routing on AS numbers looks like a final solution to the RT size problem. Indeed, such an approach could immediately reduce the RT size by an order of magnitude, since there are an order of $10^5$ IP prefixes and $10^6$ ASs in the global RT today. However, even if a protocol implementing this idea were deployed, there is no reason to believe it would change the empirically observed trend that an increasing number of small (stub) networks want to participate in interdomain routing, e.g., for traffic engineering reasons, and to do so they require their own interdomain routing addresses (AS numbers). Such small networks utilize tiny portions of the public IP address space, which implies that inevitably the total number of ASs will continue to grow at roughly the same rate as the total number of IP prefixes, and we will soon face, albeit a few years later, essentially the same problem we have today.

We learn two important lessons from this example. The first is of general significance: when considering scalability aspects of a new routing architecture, what matters is not any one-time improvement it produces, but how well it scales. A routing protocol that yields a constant reduction in RT size but the same rate of growth does not actually solve the RT size problem, it simply postpones it. Figure 1 illustrates this consideration: as network size grows, the difference between the current architecture and an architecture providing a constant-factor improvement becomes negligible. No less important is the mathematical provability of the protocol’s scaling behavior. In the case of RT size such provability implies rigorously derived worst-case (upper) bounds of the RT size as a function of the network size. The fact that we face interdomain routing scalability problems today is at least in part due to the lack of any rigorous performance guarantees embedded in the BGP design. We should not repeat the same mistake in the future.

The second lesson is more specific: organization (AS) boundaries do offer a natural level of aggregation and abstraction of routing information. It would be thus unexpected to neglect such a possibility for RT size reduction. Indeed, we adopt the idea of routing on AS numbers, and the natural level of network topology abstraction we consider in our work is thus the Internet AS-level topology graph.

Furthermore, faithful to our reductionistic spirit, we temporarily avoid discussing routing policies. T. Griffin et al.’s independent scope of work focuses specifically on policy-related problems. In addition, one design goal of their latest abstract routing protocol model [16] is explicit modularity with respect to the routing algorithm and policy components of the protocol. Thus we believe that our work on the algorithmic component can proceed in parallel and virtually independently of the vitally important policy-related research. Satisfactory results in both domains would powerfully position the research community to offer a complete solution.

To summarize this section, we assert that in order to find sustainable solutions to the global Internet routing problem, we need to investigate the scalability issues at their most fundamental level. For interdomain routing the framing question appears to be the performance guarantees of routing algorithms operating on graphs with topologies similar to the Internet AS-level topology. In particular, we are interested in rigorous upper bounds of the RT size. It turns out that compact routing is exactly what we are looking for: a research area focused on construction of efficient routing algorithms with proven worst-case performance guarantees. However, before we describe compact routing, we need to discuss stretch.

3 Routing stretch

The stretch of a routing algorithm is defined as a worst-case multiplicative path-length increase factor. More specifically, for every pair of nodes in all graphs in the set of graphs the algorithm can operate on, we find the ratio of the length of the path produced by the algorithm to the length of the shortest path between the same pair of nodes. The maximum of this ratio among all node pairs in all the graphs is the algorithm’s stretch. The average stretch is the average of this ratio on a subset of graphs.

We emphasize that stretch has nothing in common with known forms of path inflation in contemporary Internet routing. Path inflation is today’s Internet is not due to the non-trivial stretch of an underlying routing algorithm, but rather due to intra- and inter-domain routing policies, various incongruities across multiple levels of network topology abstraction (geographical, router-, AS-level), etc. [17].

In fact, we are not aware of any currently used routing protocol that would implement a routing algorithm with

Figure 1: Constant-factor improvement vs. better scaling. Scalability means effective scaling, not a one-time reduction. Although the difference in impact between alternatives to the existing architecture may be small today, in the long run a constant factor reduction is negligible compared to the performance gain from a genuinely scalable solution. Any solution that scales in essentially the same way as the existing architecture is only postponing the problem.

Note the difference between terms routing protocol and routing algorithm. The algorithm is a part of a protocol. In BGP case, for example, the protocol is BGP itself, while algorithm is path-vector.
stretch greater than 1 (stretch > 1): link-state (LS) in OSPF or ISIS, distance-vector (DV) in RIP, LS/DV hybrid in EIGRP, and path-vector in BGP are all forms of trivial shortest-path routing (stretch-1). Consider two examples: BGP and OSPF. Non-trivial policy configurations generally prevent BGP from routing along the actual shortest path, but without policies the BGP route selection process would always select the shortest paths in the AS-level graph. Similarly, non-trivial area configurations prevent OSPF from routing along the shortest paths, but routing inside an area is always along the shortest path in the weighted router-level graph.

The above examples seem straightforward but we identify them to eliminate any possible confusion between stretch of a routing algorithm and inflation of paths produced by a routing protocol. Clarifying the difference allows us to formulate both necessary and sufficient requirements for routing stretch. The sufficient routing stretch requirement is that the routing algorithm underlying any realistic interdomain routing protocol must be of stretch-1. Our reasoning behind this requirement is as follows. Consider a generic stretch > 1 routing algorithm and apply it to a complete graph, which has all nodes directly connected to all other nodes so that all shortest paths are of length 1. If the routing algorithm does not guarantee to find all shortest paths, it would imply that some nodes in a complete graph would not know about their own directly connected neighbors.

Of course, the Internet interdomain topology is not a full mesh, and it might turn out that the same routing algorithm that fails to be stretch-1 on a full mesh does in fact find all shortest paths to each node’s neighbors in realistic Internet-like topologies. We thus might also pursue the explicit task of finding a non-generic routing algorithm that is applicable only to Internet-like topologies. We do not require this algorithm be stretch-1, but it must be of stretch-1 on paths of length 1 leading to nodes’ neighbors. In other words, the necessary routing stretch requirement is that the routing algorithm under the realistic interdomain routing protocol must be of stretch-1 on paths of length 1 in realistic Internet-like topologies.

These requirements are purely practical: if a link exists between a pair of ASs, they must be able to route traffic over this link. If our sophisticated routing algorithm removes routing information about this link from the ASs’ RTs, then the ASs’ network operators will have to manually reinsert it, which counters the scalability objective of reducing the RT size. We will refer to this administrative re-adding of information about shortest paths to nodes’ neighbors as neighbor reinsertion.

The absence of a neighbor of a node in that node’s RT appears to contradict common sense, but one can verify that it occurs with the algorithms we discuss in Section 5. We emphasize that we have not had to deal with this effect in practice yet because the routing algorithms in operation today are all of stretch-1. Indeed, this effect reflects the inevitable trade-off between RT size and stretch. Intuitively, we can explain this trade-off as follows: shortest path routing implies complete knowledge of the network topology, complete knowledge suggests a lot of information, and a lot of information suggests large RTs. In order to shrink RTs, we must prepare to lose topological information, and such loss necessarily increases path lengths. In addition, the meshier the network, the more information about node neighbors there is to lose. The full mesh is an extreme example of this dilemma.

This fundamental unavoidable trade-off between stretch of a routing algorithm and sizes of RTs it generates is at the center of compact routing research going on today, but the first formalization of this trade-off was introduced many years ago in the context of hierarchical routing.

4 Why hierarchical routing will not work

The pioneering paper on routing scalability was Kleinrock and Kamoun’s [18], which introduced the idea of hierarchical routing. The key idea is to group (or aggregate) nearby nodes into areas, areas into super-areas, and so on. Such grouping is a form of the network partitioning problem. Hierarchical aggregation and addressing offer substantial RT size reduction by abstracting out unnecessary topological details about remote portions of the network: nodes in one (super-)area need to keep only one RT entry for all nodes in another (super-)area. To our knowledge, all proposals for future Internet routing architectures trying to address the RT size problem are based, explicitly or implicitly, on this concept of hierarchical routing. In fact, no other kind of RT size reduction technique has been considered in the networking literature.

Unfortunately, according to the best available data, hierarchical routing is simply not a good candidate for interdomain routing.

Indeed, in the same paper [18], Kleinrock and Kamoun were the first to analyze the stretch/RT size trade-off. They showed that the routing stretch produced by the hierarchical approach is satisfactory only for topologies with average shortest path hop-length (distance) \( d(n) \) that grows quickly with network size \( n \), which means it works well only for graphs where long paths prevail. In fact, they assumed \( d(n) \sim n^v \) with \( v > 0 \). Such graphs have many remote nodes, i.e., nodes at long hop distances from each other, and one can efficiently, without substantial multiplicative path length increase, aggregate details about topology around remote nodes, simply because those remote nodes are abundant.

Unfortunately, according to the best available data, the Internet topology does not meet those conditions. The Internet AS-level topology is a scale-free network with characteristics described, for example, in [19]. To avoid terminology disputes, by scale-free we simply mean networks with fat-tail, e.g., power-law, node degree distributions. In theory, the average distance in such topologies grows with network size much more slowly than [18] assumed: it is at most \( d(n) \sim \log n \). In practice, the average hop distance between ASs in the Internet stays virtually constant or even decreases due to increasing inter-AS connectivity [15]. According to multiple data sources, the average AS hop distance in the current Internet is between 3.1 and 3.7, with more than 80% of AS pairs 2-4 hops away from each other [19]. We call a network small-world if most of its nodes are at

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5. The word trivial is not a judgment but a reference to trivial shortest-path routing in Section 5.

6. A generic routing algorithm works correctly on all graphs.
small distances from each other. Thus the Internet AS-level topology is small-world: it has essentially no remote nodes, which is extremely bad news since the effectiveness of network partitioning depends on their abundance. In other words, the unsettling but plainly observed reality is that one cannot efficiently apply hierarchical routing to small-world Internet-like topologies.

The previous arguments might sound too general since we could still apply some generic hierarchical routing algorithm to the Internet. However, such application cannot be efficient and we must prepare to see high stretch. And indeed, simple analytical estimates \[21\] show that applying hierarchical routing to an Internet AS-level topology incurs a \(\sim 15\)-time path length increase, which, although alarming enough by itself, would also lead to a substantial RT size surge caused by neighbor reinsertion. If we accept our argument in Section 3 that any truly scalable Internet routing algorithm must have stretch as close as possible to 1, we must also accept the fact that hierarchical routing will not meet our needs. We conclude that all previous Internet interdomain routing proposals heavily based on hierarchical routing ideas\(^8\) are not realistic and, if deployed, would not genuinely scale.

5 History of compact routing

Fortunately, Kleinrock and Kamoun’s results \[18\] are the first but not the last results of research on scalable routing. The history of this research is not linear; we outline it in this section.

We have not mentioned yet that \[18\] also suffered from a problem more serious than high stretch on small-world graphs. It did not provide any algorithms to actually construct, for a given topology, a network partitioning upon which hierarchical routing can operate. Therefore, in works that followed \[18\], first L. Kleinrock himself, then R. Perlman, and then in the late 1980s and in the 1990s B. Awerbuch, D. Peleg and others, all spent much time and effort trying to salvage hierarchical routing and to find efficient network partitioning algorithms. It did not become clear that hierarchical routing does not have any future until 1999 when L. Cowen \[22\] delivered her brilliant compact routing scheme. Her scheme had four attractive features: 1) it was non-hierarchical, so required no network partitioning; 2) it was generic and so worked for any topology; 3) it had a fixed stretch of 3 for any topology of any size; and 4) it had a sublinear RT size upper bound of \(O(n^{2/3})\). Cowen’s algorithm was also beautifully simple compared to numerous hierarchical routing algorithms accumulated by that time.

In retrospect, we can say that compact routing, which is the state-of-the-art in efficient routing algorithm research today, built on numerous findings from hierarchical routing, which had been the state-of-the-art for decades. Today, compact routing is a research area in the theory of distributed computation, a part of theoretical computer science. There is no strict definition of a compact routing algorithm, or scheme, but it usually means an algorithm with a sublinear RT size upper bound—the RT size is also called local memory space, or simply space in compact routing terminology—and with stretch bounded by a constant, in contrast to many hierarchical routing algorithms for which stretch grows to infinity with network size.\(^9\)

Since 1999 progress has been much more rapid than in the preceding 22 years. In 2001, M. Thorup and U. Zwick \[23\] (TZ) improved on Cowen’s RT size (space) upper bound, bringing it to \(\tilde{O}(n^{1/2})\) while maintaining stretch of 3. This result was particularly significant because the authors had previously proven \[24\] that any routing with stretch below 5 cannot guarantee space smaller than \(\Omega(n^{1/2})\). Therefore the TZ scheme was the first stretch-3 scheme whose memory space upper and lower bounds were nearly the same (up to a poly-logarithmic factor implied by ‘\(\tilde{\cdot}\)’ in the \(\Omega\) notation). In other words, the TZ scheme was the first generic nearly optimal routing scheme of stretch 3.

The main problem with both the Cowen and TZ schemes is that they are name-dependent, meaning that topological information is embedded in node addresses which thus cannot be arbitrary. Such schemes cannot be used in dynamic topologies, since any topology change potentially requires renaming many nodes. In 2003, M. Arias et al. \[25\], delivered a name-independent, i.e., name/addresses of nodes can be arbitrary, routing scheme with a memory space upper bound of \(\tilde{O}(n^{1/2})\) and stretch of 5. In 2004, I. Abraham et al. \[26\] improved on \[25\] by decreasing stretch to 3, which makes it the first generic nearly optimal name-independent stretch-3 routing scheme.

Why do we mention stretch-3 so often? For stretch-1 (shortest path) routing, one can construct RTs at each node by storing, for every destination node, the ID of the outgoing port on the shortest path to the destination. The number of destinations is \(n - 1\), the maximum number of ports a node can have (equal to maximum possible node degree) is also \(n - 1\), and thus a maximum \(O(n \log n)\) bits of memory is required for an RT. This construction is called trivial shortest path routing. However, in 1996, C. Gavoille and S. Pérennès \[27\] showed that the lower bound of generic stretch-1 routing is also \(\Omega(n \log n)\), i.e., there is no shortest path routing scheme that guarantees local memory space smaller than \(\Omega(n \log n)\) at all nodes of all topologies. In other words, shortest path routing is incompressible. In order to decrease the maximum RT size, we must allow maximum stretch to increase. Finally, in 1997, C. Gavoille and M. Genegler \[28\] showed that for any stretch strictly below 3, the local space lower bound is nearly the same as for stretch-1 routing, \(\Omega(n)\), meaning that no generic stretch<3 routing scheme can guarantee sublinear RT sizes: the minimum value of maximum stretch allowing sublinear RT sizes is 3.

6 Compact routing applicability

The end of the last section sounds alarming: it conflicts with considerations in Section 3 where we discuss why stretch should be close to 1 for practical applicability. Do shortest path routing incompressibility and impossibility of sublinear-space stretch<3 routing mean that scalable interdomain rout-

\(^8\)Classic examples of such proposals are \[12, 11\]. Note that recent work in \[14\] advocates hierarchical routing, but the authors do not try to use it to reduce RT size. They do reduce RT size, but only by routing on AS numbers.

\(^9\)One can verify that on an \(n\)-node full mesh, for example, \[18\] produces stretch growing to infinity as \(\Theta(\log n)\).
ing with sublinear RT sizes is not achievable at all?

To answer this question, recall from Section 3 that stretch refers to the maximum path length increase among all paths in all the graphs on which a routing algorithm operates, meaning that there exists some worst-case graph\(^{10}\) on which this maximum is achieved. Recall also that all schemes mentioned in Section 5 are generic; they can work on any graph, meaning that the worst-case graph does not have to be Internet-like. We can consequently expect the average stretch of these schemes on the class of Internet-like graphs to be lower than 3. But how close can it be to 1? At first thought it seems unlikely to be close to 1 at all, since we saw in Section 4 that the stretch of hierarchical routing tends to be high on small-world graphs, and there is no reason to believe that compact routing would be drastically better. However, in 2004, \(\textbf{21}\) showed that the average performance of the first optimal stretch-3 scheme (TZ) \(\textbf{23}\) on Internet-like topologies is spectacularly better than its worst case: while its upper bounds are around 2200 for RT size and 3 for stretch, the average RT size of the TZ scheme on the real Internet topology was found to be around 50 entries (for the whole Internet!) and the average stretch was only 1.1\(^{11}\). These numbers are striking evidence that, on the same topology and under the same assumptions, compact routing dramatically outperforms both hierarchical routing \(\textbf{15}\), with its stretch of 15 and RT's of unknown sizes, and simple routing on AS numbers \(\text{(e.g., 13)}\), with RT sizes of the order of \(10^6\).

An interesting question is why compact routing turns out to be so spectacularly efficient on Internet-like topologies. There is no rigorous answer to this question yet, but intuitively we can think of a scale-free network as a dense interconnected graph, and one can verify that the stretch of many compact routing schemes, e.g., Cowen, TZ, on stars is 1. In addition, the scalability of the most efficient routing on trees—and stars are trees—is dazzling: RT sizes and RT lookup times are nearly constant (they do not grow with network size), and stretch is 1 \(\textbf{23}\). Of course, the Internet topology is not at all tree-like, since strong clustering \(\textbf{19}\) renders its treewidth high. But surprisingly, \(\textbf{29}\) finds that strongly clustered networks and networks with low treewidth both possess the set of properties allowing for remarkable performance of an important class of routing strategies.

While the preliminary findings in \(\textbf{21}\) clearly demonstrate the potential power and superiority of compact routing to everything previously considered in networking in pursuit of routing scalability, many open questions remain. In the remainder of this section we catalog the four open problems we consider most important.

The average stretch was found to be close to 1 in \(\textbf{21}\), but not 1. In fact, the average stretch does not even approach 1 in the limit of large networks. One can verify that if the average stretch does not approach 1 on scale-free graphs at least as fast as \(1 + \Theta(n^{-1/2})\), then the average number of non-shortest paths per node is such that the neighbor reinsertion from Section 5 will break the theoretical RT size upper bound of \(O(n^{1/2})\). If the average stretch does not approach 1 at all, as in \(\textbf{21}\), then neighbor reinsertion forces the RT size to go from \(O(n^{1/2})\) back to its trivial linear scaling \(O(n)\). Therefore, the stretch scaling problem is to find a compact routing scheme with satisfactory scaling of stretch, at least for length-1 paths. Such a scheme likely exists given our intuition behind why the stretch of the TZ scheme on the Internet is so low in the first place: larger scale-free networks are increasingly “star-like”.

A stronger formulation of the same problem is to find shortest path routing with sublinear RT sizes on scale-free graphs. Sublinear-space stretch-1 routing applicable to all graphs cannot exist \(\text{cf. Section 5}\), but if we narrow the class of graphs to scale-free graphs then there are no results so far that prove the non-existence of such routing. In addition, it may turn out that we can significantly decrease RT size upper bounds, a likely possibility given how far below its upper bound the RT size of the TZ scheme is in \(\textbf{21}\). In more general terms, the scale-free routing problem is to utilize peculiarities of scale-free networks to obtain non-generic algorithms optimized specifically for Internet-like topologies.

The most vital open problem, the dynamic routing problem, is to construct truly dynamic schemes. All currently existing schemes are static. A dynamic scheme would have rigorous upper bounds for its performance parameters in dynamic networks, where nodes and links can fail, be added or removed. Dynamic performance parameters include the number of control messages the algorithm generates to converge after a topology change, sizes of those messages, number of affected nodes, etc. We refer to these parameters collectively as convergence costs. Note that all currently deployed routing algorithms are essentially static algorithms applied to dynamic environments, an approach we know can be costly, e.g., the convergence costs of BGP are infinite given that it can oscillate persistently and not converge at all \(\textbf{30, 31}\). The convergence costs of BGP’s routing algorithm (path-vector) are also astronomically high, \(O(n!))\) \(\textbf{32}\). We need a solution with satisfactory bounds of convergence costs.

Unfortunately, this problem is fundamentally hard, as illustrated by the notable but pessimistic result \(\textbf{33}\) which says that even with unbounded RT sizes, there is no generic dynamic stretch-s routing scheme that guarantees less than \(\Omega(n/s)\) routing messages. Simply put, there is no generic routing scheme that scales sublinearly in the number of control packets per topology change.\(^{12}\) As in the static case we hope that narrowing the problem from the class of all graphs to the class of Internet-like graphs will yield more auspicious scaling.

An alternative shortcut is to disregard the fact that all existing compact routing schemes are static and to test them in dynamic networks anyway. The intuition behind why these schemes might still work well even in the dynamic environment lies in their ultra-optimal static performance. Since the existing name-dependent schemes are not appropriate candidates for such experimentation for reasons we mentioned in Section 5, the name-independent routing problem is to ana-

\(^{10}\)See \(\textbf{23}\) for the explicit construction of this graph.

\(^{11}\)We remind that while these numbers are overwhelming, they correspond to a one-time improvement. In the long-term, what matters is the mathematically proven scaling behavior of the scheme \(\text{cf. Section 5}\).

\(^{12}\)Although linear scaling in practically unacceptable, it is still much better than the \(O(n!)\) scaling of the path-vector algorithm.
lyze the performance of static name-independent routing schemes on dynamic Internet-like topologies. Work in this direction has already begun: in [34] the authors tested the first optimal stretch-3 name-independent routing scheme which they implemented and deployed in an overlay on PlanetLab in October 2004.

7 Conclusion

The ultimate goal of our work is to build an incrementally deployable interdomain routing protocol that will encompass not only a new routing algorithm with satisfactory rigorous bounds for routing table size, stretch, and convergence costs, but also routing policies with appropriate performance guarantees. We believe it is too early to discuss protocol details since we do not yet even have constituents with acceptable characteristics, much less understand their idiosyncrasies.

On the positive side, this quest has already begun. Current circumstances in the fields of theoretical computer science (TCS) and networking have created a rare opportunity to pursue a fundamental breakthrough in the search for truly scalable routing. Recent developments in TCS yield shockingly promising results: alternative compact routing algorithms offer dramatically superior scalability characteristics than those being used or even considered in networking. We recognize the need for a radical change in our approach to routing research in order to build on these contemporary results from TCS. The first task is to determine how applicable these results are to real-world networks.

Construction of practical, efficient, and scalable routing for the next-generation Internet is a key motivator of our work, but we recognize that we are only at the beginning of an extensive analysis of our most fundamental assumptions about routing in data networks. One such assumption is the adequacy of representing a real dynamic network using an intrinsically static construct, a graph. This assumption underlies, either explicitly or implicitly, all forms of routing we have discussed in this paper. If we discover in the future that scalable dynamic routing cannot even exist in principle within the static graph-theoretic framework constraints, then some unknown but presumably paradigm-shifting approaches to data network routing will become inevitable. Regardless of the outcome, what matters today is that we have a unique opportunity to explore a radical new path, which initially looks more promising than any previously considered approach to scalable routing.

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