In Search of Simplicity: A Self-Organizing Group Communication Overlay

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Abstract: Group communication primitives have broad utility as building blocks for distributed applications. The challenge is to create and maintain the distributed structures that support these primitives while accounting for volatile end-nodes and variable network characteristics. Most solutions proposed to date rely on complex algorithms or on global information, thus limiting the scale of deployments and acceptance outside the academic realm.

This article introduces a low-complexity, self-organizing solution for building and maintaining data dissemination trees, that we refer to as UMO (Unstructured Multi-source Overlay). UMO uses traditional distributed systems techniques: layering, soft-state, and passive data collection to adapt to the dynamics of the physical network and maintain data dissemination trees. The result is a simple, adaptive system with lower overheads than more complex alternatives. We implemented UMO and evaluated it on a 100-node PlanetLab testbed and on up to 1024-node emulated ModelNet networks. Extensive experimental evaluations demonstrate UMO’s low overhead, efficient network usage compared to alternative solutions, and ability to quickly adapt to network changes and to recover from failures.

Keywords: group communication, data dissemination, structured and unstructured overlays, performance evaluation.

1 Introduction

Collaborative applications such as conferencing, shared virtual workspaces, or multi-player games rely on group communication functionality. Recently, this functionality has been used in contexts such as peer-to-peer resource discovery \cite{1} or resource monitoring \cite{2}. Limited native multicast support in the Internet \cite{3} and application-specific requirements (e.g., reliability, message stream semantics) make application overlays an attractive alternative to IP-layer multicast \cite{4-9} to provide group communication functionalities. Application overlays \cite{4} employ participating end-systems to implement functionality not provided by the underlying communication layer or to improve the characteristics of services provided by lower network layers. When providing group communication functionality, overlays serve as support for extracting dissemination trees used to send data from each source to all destinations.

Two broad classes of overlays have emerged, differentiated by the existence of global rules (or the lack of thereof) that restrict their geometry. \textit{Unstructured overlays} allow unrestricted interaction patterns between participating nodes, while \textit{structured}
overlays impose global, regular structures. Intuitively, unstructured overlays are less expensive to create and maintain as there are no topological restrictions. Unstructured overlays have more flexibility to map on inherently heterogeneous sets of end-nodes linked by a physical network, the Internet, that displays scale-free [10] and small-world [11] characteristics. However, existing solutions for multi-source group communication based on unstructured overlays have limited scalability [12, 13] or incur large overheads [1]. On the other side, the scalability advantage offered by structured overlays [14, 15] is offset by their less efficient usage of underlying network resources and higher protocol complexity [16].

The structured vs. unstructured overlay debate is particularly relevant in a large-scale data distribution context because of the tension between scalability and efficient network usage. Our research brings new evidence to this debate by proposing a multi-source group communication solution based on unstructured overlays and extensively evaluating it against the best solutions proposed so far in both the structured and unstructured overlay classes.

While novel as a whole solution, the group communication infrastructure we propose builds on traditional, well understood building blocks. We have reached this design in our quest for simplicity. We use recently proposed heuristics [17, 18] to build and optimize an unstructured base overlay. On top of it, we use flood-and-prune techniques to select efficient, source-specific message data dissemination trees (or spanning tree): we use the implicit information contained in the duplicate messages that result from flooding to filter out redundant overlay paths. In the following, we refer to the resulting Unstructured Multi-source Overlay solution as UMO. This solution:

- has low complexity: it relies on soft-state and passive data collection to extract data dissemination trees and adapt to participating end-host and physical network dynamics. We assert that reduced complexity is a highly desirable property of distributed, large-scale systems.
- is self-organizing: independent decisions made at each node based on partial, local information result in desired global system behavior.
- is scalable with the number of sources and independent of the number of participants.
- recovers quickly from significant failures in the set of participating end-hosts and adapts to changes in the underlying network topology with minimal disruption to the service offered.
- is independent of the topology of the base overlay and of the mechanisms used to build it which makes it reusable in a wide array of situations.

This work makes multiple contributions. First, we combine in a novel way a number of traditional, distributed systems techniques to build a simple, efficient data dissemination overlay. Second, and more importantly, we show, via extensive experimental evaluations over a live wide-area testbed (PlanetLab [19]) and large emulated networks (ModelNet [20]), that although UMO uses a low-complexity protocol and nodes maintain little state, the resulting dissemination trees are more efficient than those offered by structured overlay-based solutions or by unstructured overlay-based solutions that maintain global state. Additionally, we confirm previous results regarding the relative performance of alternative overlay solutions obtained only through low-fidelity simulations by evaluating actual implementations over large-scale emulated networks. Third, we identify optimal overlay layouts and use them to quantify the overheads introduced by UMO and
alternative solutions. This offers an upper bound for potential gains achievable through better decentralized overlay construction algorithms. Fourth, we present an empirical method for choosing the parameters that drive the tradeoff between agility to adapt and stability, a tradeoff all systems that need to adapt to the evolving characteristics of their underlying platform have to decide on.

The rest of this article is organized as follows. Section 2 surveys the main challenges application-layer overlays face and the metrics employed to evaluate how well particular solutions meet these challenges. Section 3 presents the main alternative overlay topologies used to provide multi-source group communication functionality. Section 4 presents the UMO design. Implementation details are presented in Section 5 and experimental evaluations in Section 6. Section 7 surveys the related work and Section 8 concludes.

2 Overview

In this section we discuss challenges and success metrics associated with building a group communication system, state our design choices, and sketch our solution.

2.1 Challenges and Success Metrics

This section identifies the key challenges, and for each challenge, it also identifies the metrics used to evaluate success and to compare with alternative approaches.

i.) Efficient usage of underlying network resources. Data dissemination trees should map well on the underlying network. Since overlays are implemented on top of IP, the efficiency of the dissemination trees used should be compared with IP-multicast. An efficient tree minimizes: relative delay penalty (RDP), i.e., the ratio between the message propagation delay in the overlay and in the underlying network; and network stress, i.e., the number of duplicate messages generated due to mapping multiple overlay tunnels over the same physical link. These metrics are defined with respect to a common IP-layer base and have been traditionally used to evaluate data dissemination solutions [8].

ii.) Scalability is obtained by minimizing the overheads to maintain efficient distributed structures: the base overlay and data dissemination trees in this case. Two main types of overheads can be identified: overheads for estimating the conditions of the underlying network (such as latency or available bandwidth) and state maintenance overheads (such as routing table updates, connectivity maintenance, partition detection, and overlay bootstrap control messages).

iii.) Resilience. When not bandwidth-constrained, a data dissemination infrastructure should deliver each message to all destinations in spite of node failures or adaptation events. To quantify resilience, we estimate delivery rates under various failure scenarios.

iv.) Adaptation. The infrastructure should build and maintain efficient dissemination trees in spite of end-host failures and changes in the topology and state of the underlying network. Moreover, the overlay should adapt quickly to changes in the properties of participating resources and end-host and routing failures. If adaptation is a process by which a change (e.g., failure) is responded to, we can measure the ‘success’ of adaptation by tracking the evolution of metrics that characterize overlay efficiency
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(network stress, RDP) or delivered data rates. Presumably, we will typically see these metrics first drop and then increase to a new stable point. The time required to cross a certain threshold of effectiveness is a measure of agility, as is the time required to stabilize.

2.2. Design Choices

We summarize the salient design choices of our solution:

i.) Best effort service: Ideally, all nodes receive all transmitted messages. However, messages may be lost due to node crashes, overlay self-organization events, or insufficient transport capacity in the underlying network. UMO aims to provide a best effort service; reliable delivery and flow and congestion control can be implemented at a higher layer, if necessary. UMO, as most other solutions, does not attempt to provide these high-level properties because their semantics are generally application specific.

ii.) Decentralized design: Solutions that rely heavily on centralized, stable components have higher adoption barriers due to the need to define, deploy, and operate these components. Thus, we seek a solution with minimal dependence on centralized, stable components. Moreover, we attempt to minimize the state maintained at each participating host in order to limit state maintenance overheads.

iii.) Scale: We target medium scale groups with thousands rather than millions of sources. This restriction however does not apply to the number of passive participating nodes.

2.3. Solution Overview

UMO builds two layers on top of the physical network (Figure 1). First, the base overlay: the set of all logical tunnels that connect pairs of overlay nodes using physical network paths. Second, from the base overlay UMO extracts source-specific data dissemination trees: subsets of tunnels in the base overlay used to route and deliver messages generated by a specific source.

UMO starts with a random base overlay and uses a ‘short-long’ heuristic to incrementally improve it (Section 4.2.). Additionally, the base overlay provides the basic bootstrap, fault-recovery, and connectivity maintenance functionality (Sections 4.3 to 4.5). Consistent with our goal of layer independence, the heuristics and mechanisms used at the base overlay layer are independent of the mechanisms employed by higher layers.

UMO builds source-specific dissemination trees from the set of tunnels offered by the base overlay in the following way (Section 4.1): a new data source starts by flooding the base overlay. Participating nodes observe this traffic and use the implicit information contained in duplicated messages to filter-out the redundant, low-quality tunnels that generate duplicate traffic.

3 Overlay Topology Choices

In order to place UMO in context, this section presents a minimal overview of overlay topologies used to support group communication while Section 7 surveys related work in depth. Depending on the topology of the supporting overlay,
approaches to providing group communication functionality can be grouped in three broad classes: shared-tree, unstructured, and structured overlays.

### 3.1. Shared-tree Overlays

Shared-tree overlays maintain a tree-structured topology [5, 9, 21] and generally target one to many data dissemination. The tree topology makes explicit routing mechanisms unnecessary: a node simply forwards each new message on all its tunnels except the tunnel from which it received the message. Shared-tree structures, however, have major limitations: trees are fragile with respect to node failures, introduce additional delay penalties, and do not make effective use of all bandwidth available in the underlying network [22].

### 3.2. Mesh-based, Unstructured Overlays

Narada [8] and Scattercast [12] build an unstructured, initially random, base overlay mesh and employ a distance-vector routing protocol (DVRMP [23]) to extract source-specific data dissemination trees. The routing protocol provides each node with information on all other system participants and on the optimal cost and path to reach each of them. The considerable volume of data transferred to build and maintain this large state at each node significantly limits scalability. Narada, for example, is designed for groups of up to a few hundred nodes [8].

However, this approach has main advantages: first, routes are optimal for a given cost function and base overlay; and second, once detected, connectivity failures can be fixed easily using the routing information. Additionally, the information collected by the routing protocol is used by heuristics that incrementally improve the base overlay, in a solution that couples two functionally independent layers: data dissemination tree extraction and base overlay optimization.

Some peer-to-peer (P2P) applications (e.g., Gnutella) use flooding over a random base overlay to distribute messages. While simplicity is an undeniable advantage of this approach, its main drawback is inefficient network usage due to duplicate messages resulting from ignoring the underlying physical network topology [1].

### 3.3. Structured Overlays

The regular overlay structures at the base of distributed hash tables (e.g., hypercube, Plaxton mesh) can be exploited to extract dissemination trees. While originally targeted for different purposes, there is now interest for using these structured overlays to support application-layer data dissemination [14, 15, 24, 25].

Two important benefits have been asserted for this approach. First, good scalability through reduced state size at each node: structured overlay routing tables grow only logarithmically with the size of the network. Second, the ability to support multiple groups and reuse the overlay structure. These benefits however, are subject to debate. In a recent paper, Bharambe et al. [16] argue that, under realistic deployment conditions involving heterogeneous end-host and link capacities, these benefits are drastically limited: optimized dissemination trees that achieve good performance must include a large number of tunnels that are not part of the original structured overlay, thus increasing the state maintained at each node. Additionally, these tunnels limit the benefits of route convergence and loop-free properties of the original structured overlay and generate additional maintenance costs, thus limiting scalability.
4 UMO DESIGN

This section presents in detail UMO’s two functional layers as well as the techniques used to deal with node failure, adapt to network dynamics, and bootstrap the network.

Two key ideas enable nodes to operate locally and build data structures (dissemination trees) with global properties.

4.1 The Base Overlay

UMO uses relatively simple heuristics to build and maintain the base overlay: the aim is simply to include efficient data dissemination trees that can be later selected by the upper layer. This section presents a high level view of the base overlay management operations. The Appendix 10.1 presents the detailed pseudo-code.

While the base overlay is initially random, nodes optimize it incrementally, an approach common to other systems [8, 17, 26]. In keeping with our decentralization and self-organization design principles, nodes decide independently based only on local information what overlay tunnels to add or delete. As in Shen et al. [17], nodes maintain a fixed proportion $P_{short}$ (defaulting at 50%) of their tunnels short, i.e., to nearby nodes, and the other tunnels long, to distant nodes. We use a latency threshold $D_{short}$ (with a 10ms default value) to discriminate between short and long tunnels. At fixed time intervals, a node runs an optimizer task that randomly selects a small subset of participating nodes, evaluates new tunnels, and replaces its worst tunnel with a new one, if better. We limit changes to one tunnel replacement per optimizer iteration.

Short tunnels are optimized for latency: that is, a node replaces its worst short tunnel if a new shorter tunnel is found. Long tunnels are optimized for bandwidth: that is, a node replaces its worst long tunnel if it finds a new tunnel with better bandwidth. To avoid oscillations due to measurement errors or variations in network conditions, a threshold is used when deciding whether to replace an existing tunnel.

In addition, the overlay topology can adapt to heterogeneous node characteristics by defining the number of tunnels a node supports, and thus its load, to be proportional to node capacity (e.g., its access link bandwidth).

4.2 Extracting Efficient Dissemination Trees

UMO extracts efficient, source-specific dissemination trees using the implicit information from duplicated messages resulting from flooding. The Appendix 10.2 presents the detailed pseudo-code. The key idea is that an initial flooding stage allows each node to infer properties of the base overlay just by detecting duplicate messages: duplicates arrive on paths with worse properties than those taken by the first message. Once duplicates are detected, this information can be used to filter out redundant paths for efficient message dissemination. The rest of this section presents an informative example while the appendix presents in detail the protocol executed at each node.

In Figure 2 (left), nodes A, B, and C form an overlay. A is the source of a message $m_A$ that is flooded to B and C. B and C in turn flood the message on all their other tunnels. Nodes that receive a duplicate do not forward it further. Assume B receives $m_A$ first from A and then from C. B can thus infer that it has a better path from A than the one that goes through C and can ask C not to forward further A-sourced messages on the C-B tunnel.
The same mechanism, when used at C, causes B to be asked to stop forwarding A-sourced messages to C on the B-C link. Thus, nodes B (respectively C) install ‘filters’ for A-sourced messages for their tunnels to C (respectively B), and a dissemination tree as in Figure 2 (right) is extracted using only the duplicate message information that flows into the network. Note that the tree obtained with this mechanism is cost efficient with respect to the costs of sending A-sourced messages.

4.3. Dealing with Node and Tunnel Failure

Node and tunnel failures are the main potential problem once dissemination trees have been built by filtering out redundant tunnels as presented in the previous section.

Failure detection is straightforward: nodes paired by tunnels periodically exchange aliveness messages. If one node does not receive these messages for a predefined period of time, it infers that a failure occurred involving either the other end of the tunnel or the underlying network path.

Once a failure is detected the node initiates the recovery process. First, to restore the connectivity of dissemination trees that used the tunnel, the node that detects the tunnel failure resets all filters for tunnels ending at the node. Second, nodes must also deal with tunnel failures that occur further away in the overlay topology, to prevent local failures from destroying connectivity to remote nodes. To address this latter requirement, nodes that detect a failure flood a \texttt{resetRouteMessage} message with a small time-to-live that causes all receivers to reset their ‘filters’ and to eventually restart the process of tunnel selection described in the previous section. The corresponding pseudocode is presented in the appendix.

Furthermore, filters are soft-state: they expire after a certain timeout. Thus, nodes regularly revisit their decision to include or exclude a tunnel from a dissemination tree. Timeouts can be fixed parameters set based on application-specific knowledge, or can be computed adaptively, in a manner inspired by TCP timeouts. A related approach is employed in other P2P systems [1, 27] based on the intuition that the ‘age’ of a node is a good predictor for its future lifetime.

4.4. Keeping the Base Overlay Connected

UMO splits this task into two separate problems: (1) partition detection and (2) repair.

\textit{Partition detection.} As in [12, 17] to detect partitions we employ a heartbeat-based solution. A special heartbeat node that inserts messages in the network at regular intervals $T_{\text{heartbeat}}$. Nodes that do not receive the heartbeat for some multiple of $T_{\text{heartbeat}}$ conclude that they have been disconnected and initiate the repair procedure. If the heartbeat monitor dies, Saxons [17] suggests an election protocol to elect a new heartbeat source. As this protocol is unlikely to work at our target scale, we use $N$ heartbeat sources: a node is connected as long as it hears from more than $N/2$ sources. This solution tolerates $N/2 - 1$ simultaneous heartbeat source failures.

\textit{Repair.} Once a node detects it is disconnected it first flushes the set of other nodes it knows about, and tries to rejoin the network, starting from the heartbeat nodes it did not hear from or from a bootstrap node. To avoid flooding the bootstrap node when multiple nodes detect they have been disconnected simultaneously, a node waits for a random time before initiating the repair procedure.

An important optimization is preventing partitions induced by the continuous adaptation of the base overlay. To this end, nodes avoid dropping the tunnels over which
they receive heartbeats. Similarly, when a node drops a tunnel to add a new neighbor, it makes sure the new neighbor does not receive heartbeats through the tunnel that it planned to drop.

4.5. Membership Maintenance and Bootstrap

Each node maintains a random subset of identifiers of other nodes participating in the overlay. UMO employs an epidemic style solution to maintain this membership information: two arbitrary nodes contact each other, for example to decide whether they agree to establish a new tunnel; they also exchange a small random subset of identifiers of other participants in the overlay. This solution, akin to epidemic communication of membership information, results in uniform distribution of this information across the overlay, has scaled well in existing deployments (e.g., Gnutella [1] has reached more than one million nodes), and has been studied extensively [12, 17].

To join the overlay, a new node needs to be able to contact one node participating in the network. The joining node contacts the already participating node aiming to establish a new tunnel. Even if the contacted node does not have available incoming slots, it will return a set of addresses of other participants thus enabling the joining node to continue its search for nodes to connect to. In the current implementation, all nodes know the address of a fixed bootstrap node, but alternative solutions that do not rely on fixed, predefined bootstrap node are possible [28].

5. Implementation

We implemented UMO in Java. The implementation includes about 25 main application classes and about 60 auxiliary classes for a total of 5,055 lines of code.

To use UMO, an application uses a send_message non-blocking call that puts messages in the appropriate outgoing message queues at the local node. The application also needs to register a callback method that is called when messages addressed to the application arrive. The application can also register callbacks to be notified when the base overlay or the dissemination tree change.

The transport protocols used to implement UMO tunnels need to provide two properties: TCP friendliness and ability to express reliability characteristics in terms of application level frames. For convenience, in the experiments presented in this section we use TCP as a base for UMO transport protocol. We are now currently experimenting a new, UDP-based transport protocol, that provides framing, implements TFRC [29] for congestion control, and allows application to control the tradeoff between transport reliability and timely frame propagation.

To estimate available bandwidth and path latencies, we have selected netperf [30] from a large number of network measurement tools (Spruce, PathLoad, TOPP and others) for its ability to perform well when deployed on PlanetLab. Each host runs a netperf server along with UMO. We modified the netperf client to work as a library that UMO invokes through Java Native Interface.

6. Experimental Evaluation

This section presents experiments that evaluate UMO techniques described above and the effectiveness of our UMO implementation: First, in Section 6.1 we use an emulated network (ModelNet [20]) to perform extensive controlled experiments that allow us to
compare UMO with IP-layer performance and with alternative solutions using relative delay penalty and network stress metrics. Second, in Section 6.2 we explore UMO performance under real-world conditions when deployed on PlanetLab [19], a live network testbed.

For the experiments presented in this section, nodes are configured to initiate at most five tunnels and accept at most seven, thus the average node degree is ten. Half of these tunnels are configured as short, thus optimized for delay, and half long and optimized for bandwidth. The timeout for a tunnel filter is fixed at 600s. The tunnel optimization thresholds mentioned in Section 4.2 are set at their default values: 2 ms for delay and 50% bandwidth improvement. While Section 6.1.5 presents a simulation methodology and results for setting tunnel optimization thresholds, for the other parameters we are currently performing extensive sensitivity studies to gauge their impact on the overall performance of the system.

6.1. Experiments in an Emulated Environment

ModelNet [20] is an emulation environment for wide-area networks. The target application runs unmodified on a set of cluster nodes. ModelNet extracts path delay and bottleneck bandwidth from user provided network topologies and emulates wide-area network traffic conditions for communication among these cluster nodes. In order to achieve scalability, ModelNet offers tunable emulation fidelity: depending on the desired fidelity level, packet contention on shared physical links is not emulated at border routers.

We experiment with UMO in this controlled environment with three goals in mind. First, we compare the quality of the dissemination trees produced by UMO with that of trees built by alternative approaches. Second, we estimate the cost of self-organization: we benefit from having full information on the network topology and we compare UMO-generated dissemination trees with optimal trees generated by heuristics using global topology knowledge. Finally, we test UMO ability to operate and adapt when the set of participating end-hosts is dynamic.

6.1.1. Experimental Setup

We use the ModelNet suite of tools to generate physical network topologies: ModelNet in turn uses Brite [31] topology generator to generate the topology graph and assign link latencies. ModelNet classifies network links as Client-Stub, Stub-Stub, Transit-Stub, and Transit-Transit depending on their location in the network [22]. Bandwidth for each link is assigned depending on its type: Client-Stub links have bandwidth randomly assigned form the 2 to 8Mbps range, Stub-Stub links: 4 to 10Mbps, Stub-Transit links: 5 to 10Mbps, and Transit-Transit in the 10 to 20Mbps range.

End-hosts are attached randomly to stub level routers. Overlay nodes then are picked randomly from these hosts. In the experiments presented in this section, for each overlay size we ran ten simulations on ten different physical network topologies. Each topology has 4,040 backbone routers. Simulated overlay size varies from 64 to 1,024 nodes.

6.1.2. Relative Delay Penalty and Network Stress Comparison

This sub-section, starts by describing techniques to estimate relative delay penalty (RDP) then compares the quality (in terms of RDP and network stress) of UMO produced
dissemination trees with that of trees built by implementations of the alternative approaches surveyed in Section 3.

There are two approaches for estimating propagation delays, thus the RDP, in the overlay.

- The \textit{offline} approach extracts the map of the overlay and combines it with network topology information when using ModelNet (or with delay estimates when on PlanetLab) to compute, offline, the delay for each overlay path.
- The \textit{online} approach estimates propagation delays through the overlay itself: once the dissemination trees are extracted: a node sends a special \textit{ping} message to which each participating node replies. Replies are propagated back to the source through the overlay. Delay estimates using this method are inherently more pessimistic: the source and intermediary nodes need to process, in sequence, a potentially large number of replies.

For ModelNet experiments these two approaches yield similar results. We discuss the differences we observe on PlanetLab between RDP estimations using these two approaches in Section 6.2.

To compare the quality of the dissemination trees produced by UMO with that of trees built by alternative approaches, we use two sets of comparisons: First, we perform a head-to-head comparison of UMO with Macedon-generated [32] implementations of alternative approaches running on the same emulation platform. Second, we compare UMO performance with that of alternative approaches as reported in a previous simulation-based study by Jain et. al [33]. In this latter comparison, we use ModelNet and attempt to reproduce the physical topologies used by Jain [33] in order to offer a meaningful comparison base.

Macedon [32] is a code-generation tool for overlays: Macedon generates overlay implementations from high-level functional specification of overlay behavior. In its latest version (v1.2.1), Macedon offers specifications for one-to-many data distribution based on shared trees (a random tree and a solution based on Overcast [5] protocol) and on structured overlays (two variants of the Scribe protocol [14]). We have instrumented the generated code to extract the dissemination trees these solutions build at runtime and we compare them with trees built by UMO.

Figures 3 and 4 summarize the results of this comparison for overlays varying from 64 to 1024 nodes. These results show that UMO performs better than the alternative solutions mentioned above. In all experiments the 90%-tile RDP offered by UMO is lower (thus better) than that offered by alternative solutions (Figure 3). On average, the 90%-tile RDP is 29% better than structured overlay solutions based on Scribe, 58% better than for random trees, and more than five times better than for Overcast. We note that the two versions of Scribe available (implementing optimizations proposed by groups at Rice University and Microsoft respectively) performed similarly. We were unable to run Scribe with more than 512 nodes due to a file descriptor leak in the Macedon implementation.

In part due to our configuration to use similar fan-outs for the dissemination trees, all solutions we test offer comparable \textit{maximum link stress} (Figure 4). The exception is the random trees which present a much more accentuated growth of maximum link stress for large overlays. Note that, although Overcast appears to produce a slower increase in link stress for large overlays, this result is achieved using a distributed lock to sequence
network measurements, a technique that is clearly non-scalable. (In fact, the time to bootstraps a 1,024 node Overcast overlay grows as large as six hours.) Without using the distributed lock mechanism the link stress evolution is in line with that produced by UMO and Scribe.

![Figure 3: 90%-tile RDP for UMO and alternative solutions for 64 to 1024 node overlays. Each point presents, average values from at least 10 runs over different physical topologies. M stands for Macedon implementation.]

![Figure 4: Maximum link stress for UMO and alternative solutions for 64 to 1024 node overlays. Each point presents average values from at least 10 runs (20 for UMO), while the error bars for UMO present min. and max. values.]

The second set of experiments compares UMO performance with that of alternative approaches reported by Jain et al. [33] in a previous study. Jain considered three unstructured overlays (Narada [8], Nice [6], and a power-law overlay that is mapped randomly on the physical topology) and structured overlays employing various mapping heuristics.

We attempt to reproduce the physical topologies used the study by Jain et al. [33] to offer a sound comparison base. Figure 5 and 6 summarize the results of this comparison for overlays varying from 64 to 1024 nodes. These results show that UMO generally performs at least as well as other alternatives: The 90%-tile RDP offered by UMO is better than that obtained using realistic structured overlays (i.e., structured overlays that do not assume a global view when mapping on the physical network). Compared to solutions that assume global view for optimization (such as Narada and the idealized structured overlays), the 90%-tile RDP offered by UMO is slightly higher, thus worse (Figure 5). In all experiments UMO offers lower (thus better) link stress than Narada, structured overlays, and naïve flooding on power-law random graphs (Figure 6).
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Figure 5: 90%-tile RDP for UMO and alternative solutions for overlay size varying from 64 to 1024 nodes. For UMO, Narada, and flooding, each point presents, average values from at least 9 runs (20 for UMO), while error bars present min and max values. Structured overlay results (labeled as DHT in the plot) present the average RDP for the best of three heuristics considered by Jain while the performance of alternative heuristics is presented in the error bars. Non-UMO results are extracted from Jain et al. [33].

Figure 6: Maximum link stress for UMO and alternative solutions. Overlay sizes vary from 64 to 1024 nodes. Each point presents average values from at least 9 runs (20 for UMO), while the error bars present minimum and maximum values. Non-UMO results are extracted from Jain et al. [33].

For clarity, Figures 5 and 6 do not reproduce Nice [6] performance results reported by Jain et al. Jain’s results show that, compared to Narada, Nice incurs 22% to 60% higher overheads in terms of RDP and performs similarly in terms of network stress. Thus Nice performs similarly to UMO in terms of RDP and worse in terms of network stress.

We note that the Scribe performance observed in our experiments is slightly better than that predicted by the decentralized heuristics investigated by Jain (but still much worse than that of idealized heuristics using global knowledge). We attribute this situation to two reasons: first, Scribe enhances the structured overlay with ‘shortcuts’ to improve the characteristics of the dissemination trees extracted, a heuristic not explored by Jain et al. [33]. Second, the heuristics to improve overlay mapping and message routing in structured overlays have received significant attention since Jain et al. [33] was published.

We note that Castro et al. [34] concludes that dissemination trees based on Pastry (the structured overlay Scribe uses) offer better performance in terms of relative delay penalty and network stress than solutions based on M-CAN [24]. Since UMO performs better than Scribe, Castro’s study gives us confidence that UMO performs better than a larger class of structured overlay based solutions.

Summary: The experiments we have presented support two conclusions: First, we show that it is possible to collect data passively, and, based on this data build, in a fully decentralized manner, efficient dissemination trees from unstructured overlays. Second, we demonstrate that although UMO uses significantly simpler heuristics than those used by alternative solutions, the data dissemination trees extracted have better or comparable performance.

6.1.3. Cost of Self-Organization

This section attempts to answer two intertwined questions:
First, we attempt to estimate the cost of self-organization: How do dissemination trees built by the self-organizing UMO solution compare with optimal trees extracted using centralized heuristics that use full knowledge about the physical topology? The performance of these optimal trees serves as upper bound for the achievable performance.

Second, we attempt to understand where to direct future effort to improve UMO heuristics: Which of the two UMO layers, the base overlay layer or the tree extraction layer, introduce the largest efficiency losses?

In order to answer these questions, we compute, using full topological information, hypothetical dissemination trees optimized to minimize relative delay penalty as described below. We note that computing these trees are variations of the Steiner tree problem [35], and, although we have not proven it formally, we believe that algorithms that find the optimal solutions are NP-complete. In the following, by ‘optimal’ solution we mean the best solution discovered by the polynomial-time approximation heuristic we describe.

- The optimal dissemination tree (or spanning tree) that can be extracted from the base overlay UMO builds. We start from base overlay topologies captured during UMO runs and use Dijkstra’s shortest path algorithm to compute optimal dissemination trees with respect to propagation delays. (The corresponding plots are labeled BASE in Figure 7).

- The optimal dissemination tree that can be extracted from a base overlay whose construction has also been optimized using global knowledge heuristics. The base overlay is built using the following heuristic: initially all nodes add maxdegree tunnels to their nearest neighbors in terms of delay; if the graph is not connected after this step, the heuristic iteratively picks one node at random, deletes its worst tunnel and adds one to the next closest neighbor in terms of delay until the graph becomes connected. On top of this base overlay dissemination trees are built using Dijkstra’s algorithm. (The corresponding plots are labeled BESTBASE in Figure 7).

- The optimal maxdegree out-degree limited dissemination trees built on top of the complete graph. This heuristic starts from a designated root node and builds a shared tree in a greedy fashion by adding, at each step, the shortest possible tunnel that expands the tree. The only difference from the minimum spanning tree algorithm is that node degree is limited to maxdegree. Note that this heuristic will always produce trees with better characteristics than those extracted from a maxdegree-limited base overlay. This reflects the difference between single source and multi-source data dissemination overlays under the same maximum node degree constraint. (Plots labeled OPT in Figure 7.)
Figure 7 presents the average 90%-tile and median RDP for disseminations trees built using UMO on ModelNet and using the three heuristics described above for 20 data sources for each of the five overlay sizes. These experiments present the distribution of performance loss generated by the two UMO layers. The yardstick is the performance of centralized, global-knowledge heuristics. Averaged over the five overlay sizes we experiment with, the 90%-tile RDP of UMO is 15.1% less than that of the optimal trees extracted from an optimal base overlay. This performance degradation has two components: 5.3% is due to the non-ideal base overlay and 9.8% is due to the non-ideal dissemination tree. In terms of median RDP however, the total performance loss is only 5.4%, almost entirely localized at the dissemination tree extraction layer. A second observation is that, as expected, dissemination trees optimized for a single source (OPT) offer significantly better performance in terms of RDP.

Summary: These experiments support two conclusions: First, UMO has low overheads when compared to ideal solutions that use heuristics based on global views of overlay membership and network properties, thus they support our claim that it is possible to use flooding and passive data collection to extract efficient data dissemination trees from unstructured overlays. Second, two thirds of these overheads are concentrated at the tree extraction layer.

6.1.4. UMO Under Churn
An important characteristic of any distributed system designed to be deployed on a real-world platform is its ability to operate in spite of component failures. In this section, we evaluate UMO’s ability to deliver messages under ‘churn’: the continuous process of node arrival and departure.

The performance metric we employ is the ratio of messages actually delivered to the number of messages that ideally should have been delivered under churn. In order to compute the number of messages that should have been delivered under churn, we keep track of all node join/crash events as well as all message generation events. For each receiver $R$ and for each message $m$ generated by source $S$ at time $T_{S(m)}$ we estimate that the message should have been delivered at $R$ if the node joined the network before the generation time $T_{S(m)}$ and left the network after $T_{S(m)} + T_{prop}$ where $T_{prop}$ is an estimated upper bound for overlay propagation time (set conservatively at 5s in the experiments we report here). In other words, node $R$ should receive a message issued at time $T_{S(m)}$ if: $T_{R(join)} < T_{S(m)} < T_{R(leave)} - T_{prop}$.

To model churn, we use independent node failures controlled by a Poisson process. This model is based on studies of user behavior in multicast groups on the MBone [36]
and in file sharing applications [37] and has been extensively employed [26, 38, 39]. As a result of the Poison process, node lifetimes are exponentially distributed. In experiments, we vary the median node lifetime from 300s to 7200s to infinity (no failures). Studies of various file-sharing networks report median node lifetimes between 10 minutes [40] and one hour [37, 41]. In our experiments, a new node joins the overlay 10s after a node failure to keep the size of the overlay constant.

Consistent with our aim to gauge UMO behavior in an unfriendly environment, we model crash-like failures as opposed to graceful (announced) node leaves. This inherently leads to higher loss rates: unlike for announced leaves, where it is possible to flush node buffers and exit gracefully, under a crash model messages are lost when nodes crash with non-empty queues.

Figure 8 presents the results of three sets of experiments with 128, 256 and 512 nodes, respectively, running on ModelNet. Each node inserts small messages into the network at a rate of one message every 5 second (so the system will deliver up to 52k messages/second). We use small messages as we attempt to evaluate the ability to timely detect node crashes, repair the overlay structure, and maintain the overlay connected, while we are less interested here in the ability to evaluate the transport capacity.

As Figure 8 shows, for 512 nodes with 5-minute average lifetime (implying perhaps unrealistically high failure rates of 1.7 failures per second on average in the whole system) 97.72% messages are delivered on average. Under moderate failure rates of 1-hour average node lifetime (translating, to one failure every 7s on average in a 512 nodes system) more than 99.9% messages are delivered on average over the whole experiment. With no node crashes, fewer than one message in 100,000 is lost.

How do these results compare with the performance of other systems? We attempted to evaluate, under the same scenario, the performance of the three other data dissemination overlays provided by Macedon and mentioned in the previous section. Unsurprisingly, the random tree solution performs fairly well as the cost of restructuring the overlay after a node failure/join is minimal: the failure rate stays above 99% for all experiments with 512 nodes. However, Macedon implementations of Overcast and Scribe do not handle failures: they become unusable even under low failure rates. (We believe this problem is an implementation shortcoming and not an inherent characteristic of these classes of solutions).

**Summary:** Although UMO does not include explicit resiliency mechanisms, it is able to recover quickly from node failures and performs well under churn.

### 6.1.5. Agility vs. Stability: Bootstrap Convergence

The ability to converge quickly to a stable state with good properties is an important characteristic of systems that operate in a dynamic environment. In this section, we
assume the characteristics of the underlying network are stable and we investigate base
overlay convergence after bootstrap. First, as a consequence of the greedy base overlay
construction strategy where each node, at each time-step, improves its existing tunnels,
the base overlay will always converge to a stable state when no external events occur
(i.e., no node failures and no variation in the underlying network characteristics).

Second, we examine the tradeoff between convergence time and the quality of the stable state to
which the base overlay converges. The variables that determine the shape of this tradeoff space are the
thresholds that trigger a tunnel change: As we mention in Section 4.2, a node replaces an existing short tunnel only if the
new tunnel offers at least $\text{DELAY}_{\text{THRESHOLD}}$ ms. lower delay and replaces a long tunnel
only if the new tunnel offers at least $\text{BW}_{\text{THRESHOLD}}$ more bandwidth.

<table>
<thead>
<tr>
<th></th>
<th>$\text{DELAY}_{\text{THRESHOLD}}$</th>
<th>$\text{BW}_{\text{THRESHOLD}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low threshold</td>
<td>0.5 ms</td>
<td>10%</td>
</tr>
<tr>
<td>High threshold</td>
<td>8.0 ms</td>
<td>75%</td>
</tr>
</tbody>
</table>

Table 1: High and low threshold values for tunnel adjustment.

Figure 9 and 10 explore the impact of these threshold values on convergence time,
number of reconfiguration events, and the quality of the stable state to which the base
overlay converges. These figures present averages over 10 runs for a 1024-node overlay
for the two extreme sets of threshold values presented in Table 1. At each iteration step, a
node probes the network path to ten other overlay nodes, and attempts to replace one
short tunnel and one long tunnel. Results are presented in terms of number of iterations,
to factor out the duration of a single iteration which is largely determined by the
effectiveness of the probing technique.

As expected, higher thresholds for tunnel adjustments lead to faster convergence
and a more stable overlay (i.e., fewer reconfiguration events). As Figure 9 shows, for
high threshold values, the total rate of reconfiguration events drops to less than one event
per time step for the 1024-node overlay after only 10 time-steps, while for low
thresholds, the convergence rate is significantly slower: reconfiguration events rate drops
to the same level only after 31 time-steps. The total number of reconfiguration events is
reduced by more than half when using high thresholds.

The difference in convergence time is also reflected in the characteristics of the
stable state obtained using the two configurations above. When using high threshold
values, the average tunnel latency is 6.8% worse and the average tunnel bandwidth is
18% worse than when using low thresholds. However, this small degradation in the
resulting base overlay quality is acceptable to obtain a more stable base overlay.
Moreover, the loss in performance is attenuated when actually extracting dissemination
trees from the stable base overlay: 90%-tile RDP is only 4.45% worse.

**Summary:** We present experiments that correlate stability: i.e., the quality of the base
overlay UMO converges to, and agility: i.e., the speed of the convergence process. These
results can be used to tune the parameters that determine node sensitivity to changes in
the environment to achieve desired levels of service depending on the characteristics of a
specific deployment platform.
6.1.6. Summary of ModelNet Experiments
We have used ModelNet, a wide area network emulator to evaluate UMO performance and compare it with that of alternative approaches. Direct comparisons on ModelNet and comparisons with previously published results support our claim that the dissemination trees produced by UMO have better characteristics (better RDP for the same stress) than those built by alternative approaches (Section 6.1.2). Additionally, the performance degradation brought by the simple UMO heuristics based on local information is small when compared with heuristics that employ global topological information to extract optimized dissemination trees (Section 6.1.3). Finally, we have demonstrated the ability of UMO to operate in dynamic environments and to adapt when the set of participating end-hosts is dynamic (Sections 6.1.4 and 6.1.5).

6.2. PlanetLab Experiments
We also ran multiple experiments on PlanetLab [19], a live, wide-area, network testbed. Our aim is to understand how well UMO operates in a real environment. Due to lack of space we limit here to present results from three experiments: first, we evaluate the difference between online and offline RDP estimates when using PlanetLab, second, we present throughput results from a multi-source data dissemination experiment using 60 PlanetLab nodes, and, third we evaluate agility in dealing with the failure of a sizeable number of network participants when deployed over a live testbed.

6.2.1. Online and Offline RDP Estimates
As we mentioned in Section 6.1.2 RDPs can be estimated online, by directly measuring the time messages travel in the overlay, or offline, by mapping the overlay to point to

Table 2: The difference between on- and off-line RDP estimates for PlanetLab experiments. For ModelNet the difference is insignificant.

<table>
<thead>
<tr>
<th>Delay estimate</th>
<th>Offline</th>
<th>Online</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%-tile RDP</td>
<td>2.53</td>
<td>4.96</td>
</tr>
<tr>
<td>90%-tile RDP</td>
<td>1.95</td>
<td>3.78</td>
</tr>
<tr>
<td>Median RDP</td>
<td>1.22</td>
<td>2.11</td>
</tr>
</tbody>
</table>

Figure 9: Average tunnel delay of short tunnels, convergence time, and number of reconfiguration events and for low and high values of reconfiguration thresholds.

Figure 10: Average tunnel bandwidth of long tunnels, convergence time, and number of reconfiguration events and for low and high values of reconfiguration thresholds.
point delay measurement between nodes. As PlanetLab nodes are heavily loaded (load is often above 10), the delays between the intervals when the application is scheduled can be large, sometimes in the same order of magnitude as IP-layer latencies. Consequently, the RDPs computed using online delay estimates (right column in Table 2) are significantly larger than when computed offline. We have not observed such delays when running on ModelNet, even when 15 copies of our application ran concurrently on the same physical node. Thus, we believe that the larger online RDP estimates are simply a result of high, sometimes transitory, load on PlanetLab nodes.

6.2.2. **Throughput on PlanetLab**

Figure 11 presents received data rates at each destination when all 60 nodes participating in the experiment send data at rates varying from 2kbps to 16kbps (resulting in aggregate rates between 120kbps and 960kbps). Nodes are located at distinct sites on three continents. Message size is 4KB for all experiments.

**Figure 11**: Multi-source performance. Each of 60 nodes sends data at rates from 2kbps to 16kbps. The graph presents received data rates at each destination. Nodes are ordered in increasing order of their received rates.

**Figure 12**: Adaptability. RDP and maximum link stress evolution for a data dissemination tree rooted at one random node. 900s after the 64-node overlay is started, 10 nodes fail during a 120s interval. The 10 nodes then rejoin 900s later, again during a 120s interval.

6.2.3. **Agility: Repair Time**

Using the same physical topology and a 64-node overlay, we explore UMO’s ability to operate in a dynamic environment. We consider a case when 10 nodes fail then rejoin the overlay 900s later. Both failure and join events are distributed over a 120s interval: seconds 1000 to 1120 for failures and 2020 to 2140 for joins on the timescale in Figure 12 presents the evolution of RDP and maximum link stress. 900s after bootstrap, RDP and stress are already close to their stable values. Since node failures are distributed over a relatively large interval, the base overlay recovers from these failures quickly and the RDP increase is not significant. Maximum link stress actually decreases as fewer participating nodes lead to fewer tunnels mapped to physical network links. The impact of nodes joining in is larger as new nodes take time to discover to which existing nodes to create overlay tunnels (Figure 12).
7 Other Related Work

In addition to the overlay-based data dissemination solutions presented in Section 3, we acknowledge related work in two other contexts: flood-and-prune techniques and high-bandwidth data-distribution.

7.1. Flood-and-Prune Techniques

Flood-and-prune techniques have been used at layers 2 and 3 in the network stack with various degrees of success and reflecting specific deployment assumptions.

At the data link layer (OSI layer 2), bridges employ a “spanning tree protocol” [42] to extract a shared dissemination tree from a non loop-free local network. UMO’s solution is different in two respects: first, the trees constructed are source-specific while the algorithm above builds a shared tree. This way UMO offers better use of resources (e.g., transport capacity, delay) available at the lower layer at the cost of maintaining additional state at each node. Efficient use of these resources is of lower concern in LAN deployment scenarios. Second, UMO builds trees by passively listening to actual traffic, without using per-tree control messages. UMO’s solution, based on caches of recently received message identifiers, is enabled by larger memory available at end-hosts and application-level frames, which enable a coarser granularity than IP packets.

At the network layer, two commonly used routing protocols, DVMRP (the Distance Vector Multicast Routing Protocol [23]) and DM-PIM (Dense-Mode Protocol Independent Multicast [43]), use a flood-and-prune technique on top of already selected dissemination trees. The main difference when compared with UMO lies in deployment assumptions: DVMRP and DM-PIM are deployed across the Internet to extract single-source group-specific dissemination trees. This way, all Internet routers participate in all the tree extraction mechanisms (which implies flooding and holding state for pruning) for all groups, even when routers do not serve any end-hosts interested in these groups. UMO, in contrast, builds per group overlays and state is maintained at only participating end-hosts: thus, as for all application-layer data dissemination solutions, state is moved to the edges of the network and hosts pay a direct cost only when participating.

7.2. High-Bandwidth Data Distribution

A number of applications target high-bandwidth data distribution. Both Bullet [22] and SplitStream [44] assume a single source scenario.

Bullet establishes multiple trees rooted at the same source and disseminate different chunks of data. By using multiple trees, Bullet reduces the need to perform expensive bandwidth probing for tree optimization. Bullet’s solution works best for single source distribution of large-files: it assumes that the application is insensitive to additional transfer delays, that delivery order of various data blocks is not important, and that the additional overhead incurred by coordinating multi-path data delivery is amortized over a large file size. UMO is designed for multiple source applications and assumes perishable data (e.g., conferencing, media streaming) in context where additional delays and message re-ordering are important concerns.

The motivating assumption for SplitStream [44] is that, in a cooperative scenario, nodes should have similar loads and, as a result, a data dissemination tree is not the appropriate solution since interior tree nodes bear the distribution load. Thus, SplitStream employs a solution similar to Bullet’s: it uses multiple trees, this time based on a
structured overlay. UMO assumptions are different: we believe that since participating hosts are inherently heterogeneous a cooperative solution should assign load proportional to node capabilities. It is possible to add, on top of this, a system that rewards the high volume nodes.

8 CONCLUSIONS

Group communication primitives are key building blocks for a large variety of distributed applications. However, creating and maintaining the distributed structures that support these primitives is challenging, particularly when network and node characteristics are transient.

UMO, the distributed, multi-source, data dissemination system we propose, is based on a simple approach to extracting source-specific dissemination trees from an unstructured overlay. This solution offers two important properties: first, it decouples the overlay construction and maintenance mechanism from the tree-extraction mechanism, allowing for separate component optimization. Second, it relies on soft-state and passive data collection to adapt to the dynamics of the physical network, resulting in low protocol complexity and low overheads. Our experimental and analytical evaluations demonstrate low communication overhead, efficient network usage compared to alternative solutions, and ability to adapt quickly to network changes and recover from node failures.

More importantly, we show that a low-complexity design can lead to a self-organizing, scalable, and adaptive overlay with performance generally better than that offered by more sophisticated solutions and, additionally, with low overheads compared to idealized solutions based on global resource views. Reduced complexity is a highly desirable property of distributed, large-scale systems. When two mechanisms offer similar efficiency for comparable costs, the discriminating factor is complexity. Additionally, in production environments an increasing premium is placed on deployable, manageable, in other words simple systems.

9 REFERENCES


42. Tanenbaum AS. *Computer Networks*. Prentice Hall, 1996.


10 **APPENDIX**

This appendix presents pseudocode for the two UMM layers: the base overlay management layer and the dissemination tree extraction and maintenance layer.

10.1. **Base overlay management.**

This section presents the pseudocode for the main thread in charge with the base overlay management. At each node, the thread operates at regular time intervals (of duration OPTIMIZER_THREAD_DELAY). It first selects a set of potential neighbors, evaluates the network conditions to these nodes, and sorts these potential tunnels according to their quality. Then, if a potential tunnel in this set is better than an existing one, the new tunnel is added to the overlay and the existing tunnel removed.

```plaintext
while (true) do:
    connCandidateSet = randomCandidates (MAX_CANDIDATES)
    foreach conn in connCandidateSet do:
        // probe the network path for each possible connection
        // and use exponentially weighted moving averages so smooth measurement errors.
        evaluatePotentialConnection (conn)

    // order the connection set in decreasing order of their potential
    sort(connCandidateSet)

    foreach conn in connCandidateSet do:
        // try to replace the worst existing short connection
        // Note: uninitialized local tunnels have infinite delay
        if isShort(conn) then:
            if (conn.delay < worstCurrShortTunnel.delay – DELAY_THRESHOLD) then:
                if (createNewConnection (conn)) then:
                    adjustConnectionsNumber()
                    delete (worstCurrShortTunnel)
                    break;

        // try to replace the worst existing long connection
```
// Note: uninitialized local tunnels have 0 bandwidth
if isLong(conn) {
    if (conn.bw < worstCurrLongConn.bw * BANDWIDTH_THRESHOLD) then:
        if (createNewConnection (conn)) then:
            adjustConnectionsNumber();
            delete (worstCurrShortTunnel)
        break;
}
wait (OPTIMIZER_THREAD_DELAY)
end while

10.2. Dissemination tree extraction and maintenance
To maintain the build and maintain the dissemination dissemination trees, each node uses
three data stores for state. These data stores are soft-state in the sense that the data items
are inserted with associated timeouts. When a timeout expires, the data store simply
flushes the associated data item.
- A data store for IDs of received messages and the tunnel they arrived on: idStore (id, conn,
timeout). This data is used to extract dissemination trees from the base overlay (otherwise
said, to detect potential cycles in source-specific dissemination trees)
- A data store for tunnels that have been filtered out by remote nodes: tunnelFiltered (source,
    conn, timeout). This, combined with the data on the next bullet, is the data that actually
    represents the dissemination trees.
- A data store for tunnels that have been filtered out by local nodes: tunnelFilteredLocal
    (source, conn, timeout).

The pseudocode below describes the reaction of a UMM node to various events: receiving
a message, detecting a cycle, receiving a message from another tunnel that a cycle has
been detected, detecting a failed tunnel.

event dataMessage(m, conn):
    // a new message is received
    oldConn = idStore.put(m.ID, conn, TIMEOUT_IDSTORE)
    // if this was a new ID put into the idStore
    if (oldConn == NULL) then:
        // then deliver to application and propagate the msg.
        callCallback (deliverMessageCallback, m)
        if (m.ttl – – <= 0) then:
            return
        foreach c in localNodeConnections do:
            if (not c in tunnelsFiltered) and (c != conn) then:
                send (m, c)
            else { // this was a duplicate so:
                // ask the node at the other of the connection not to send
                // messages from the same source again
                // (if the connection is active)
                if oldConn.active() and (oldConn not in tunnelFilteredLocal) then:
                    send (new dropRouteMessage (m.scr), conn)
                    tunnelFilteredLocal.put (m.scr, conn, TIMEOUT_TUNNEL)
            }
    }
}

event dropRouteMessage (m, conn):
    // the node at the other end of the tunnel has detected a cycle
    tunnelsFiltered.put (m.scr, conn, TIMEOUT_TUNNEL)

event failedConnection (conn):
    // when a tunnel failure is detected then spread a resetRouteMessage
    // with a small time to live to reset caches and rebuild the tree
    m = new resetRouteMessage (RESET_TTL)
foreach c in localNodeConnections do:
    send (m, c)
    tunnelFilteredLocal.reset(c)
    tunnelFiltered.reset()

event resetRouteMessage (m, conn):
    // only for new messages
    if (NULL == idStore.put(m.ID, conn, TIMEOUT_IDSTORE)) then:
        tunnelFiltered.reset(conn)
        if (m.ttl -- <= 0) then:
            return
        foreach c in localNodeConnections do:
            send (m, c)
            tunnelFilteredLocal.reset(c)