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CYCLON: Inexpensive Membership Management for Unstructured P2P Overlays

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Unstructured overlays form an important class of peer-to-peer networks, notably when content-based searching is at stake. The construction of these overlays, which is essentially a membership management issue, is crucial. Ideally, the resulting overlays should have low diameter and be resilient to massive node failures, which are both characteristic properties of random graphs. In addition, they should be able to deal with a high node churn (i.e., expect high-frequency membership changes). Inexpensive membership management while retaining random-graph properties is therefore important. In this paper, we describe a novel gossip-based membership management protocol that meets these requirements. Our protocol is shown to construct graphs that have low diameter, low clustering, highly symmetric node degrees, and that are highly resilient to massive node failures. Moreover, we show that the protocol is highly reactive to restoring randomness when a large number of nodes fail.

KEY WORDS: Membership management; peer-to-peer; epidemic/gossiping protocols; unstructured overlays; random graphs.

1. INTRODUCTION

The growth of the Internet in terms of size and speed, as well as the plethora of network applications and services that have been deployed in the last few years clearly indicate a shift from the traditional client–server model to that of highly distributed, peer-to-peer (P2P) systems. The main philosophy behind these systems is communal collaboration among peers: sharing both duties and benefits. By distributing responsibilities across all participating peers, they can collectively carry out large-scale tasks in a simple and generally scalable way, that would otherwise depend on expensive, dedicated, and hard to administer centralized servers.

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A distinguishing feature of P2P systems is that the peers jointly maintain an *overlay network*. Unlike traditional layer-3 networks, the structure of these overlay networks is not dictated by the (often fairly static) physical presence and connectivity of hosts, but by *logical relationships* between peers. In particular, P2P overlay networks are generally designed to handle a much higher rate concerning the joining and leaving of nodes, while at the same time assume that membership behavior is roughly the same for all nodes. In other words, they are designed to handle highly dynamic, symmetric networks. Overlay management is therefore a key issue in designing P2P systems.

There are currently two main categories of P2P systems in terms of overlay management. Structured P2P systems impose a specific linkage structure between nodes. Distributed Hash Tables [1] are typical examples in this category. They link peers based on their IDs in a way to enable efficient ID-based routing among them. In contrast, in unstructured P2P systems, peers are not linked according to a predefined deterministic scheme. Instead, links are created either randomly (as is typically done in Gnutella), or are probabilistically based on some proximity metric between nodes (i.e., semantic proximity, leading to what are known as semantic overlay networks). Unstructured P2P systems are primarily designed to support rapid information dissemination and content-based searching in highly dynamic distributed environments.

In this paper, we concentrate on gossip-based unstructured P2P systems [2]. These systems aim at exploiting randomness to disseminate information across a large set of nodes. A key issue is to keep the overlay connected even in the event of major disasters without maintaining any global information or requiring any sort of administration. Connections between nodes in these systems are highly dynamic. Gossiping networks generally exhibit self-healing behavior with respect to major network disasters. It has also been observed that some of these overlays exhibit properties of small-world and scale-free networks [3, 4]. However, in many cases it is better to construct overlays that are close to random graphs [5].

Gossip-based unstructured overlays can be used as a building block in a variety of network management applications, especially when highly dynamic environments are anticipated. A good example is self-monitoring in large-scale networks, where each node is charged with monitoring a few random others, sharing the monitoring cost. An appropriately chosen overlay management algorithm can ensure load fairness, and can guarantee that no node is left unattended, resulting in a robust self-monitoring system. Another example is our prior work on managing routing tables in very large P2P networks [6]. Stavrou et al. [7] suggest management of flash crowd crises by disseminating information over gossip-based unstructured overlays. In [8], we build on the research presented in this paper to maintain links between semantically related peers, and we show that it substantially enhances distributed searching for content (i.e., in file-sharing applications).

The problem we address is that of building and maintaining overlays with properties suitable for diverse applications like the aforementioned ones. More specifically, we are looking into inexpensively building and maintaining very large, connected overlay networks that exhibit important properties of random graphs. These properties should be maintained even in highly dynamic environments. In essence, we are interested in inexpensive membership management, in the sense that any disruption of the overlay's properties resulting from joining or leaving nodes should be quickly and efficiently corrected. We assume that nodes maintain a small, partial view of the entire network. Our starting point is the view exchange protocol described in [7]. This so-called shuffling protocol ensures that connectivity of the overlay is maintained as long as membership does not change.

We make two contributions. First, we provide an experimental analysis of the basic shuffling protocol for large networks, examining properties such as clustering and node degree distribution. These experiments have not been conducted before, and, in particular, not on large networks. We demonstrate that shuffling is indeed a promising exchange protocol.

Second, and most importantly, we describe CYCLON,[3] a complete framework for inexpensive membership management. CYCLON introduces an enhanced version of shuffling, which results in node-degree distributions that exhibit better properties than those found in overlays resulting from basic shuffling, or even in random graphs. Moreover, it includes better, in terms of efficiency and quality, management of node additions and removals, which allows us to establish truly inexpensive membership management that does not disrupt the randomness of the overlay network.

The paper is organized as follows. We start with explaining the basic protocols underlying CYCLON in Section 2, followed by an analysis of basic properties in Section 3. The effects of adding and removing nodes are discussed in Sections 4 and 5, respectively. CYCLON's robustness in the presence of (massively) failing nodes is discussed in Section 6. Section 7 provides an estimation of the protocol's cost with respect to network traffic. Section 8 demonstrates CYCLON's utility in a variety of applications. Related work is presented in Section 9, and we conclude in Section 10.

2. THE PROTOCOL

2.1. Basic Shuffling

The basic shuffling algorithm, introduced in [7], is a simple peer-to-peer communication model. It forms an overlay and keeps it connected by means of an

[3]The name CYCLON was inspired by the protocol's power in mixing nodes in the network, sort of like a tornado. It is also inspired by the Greek origin of the word, *kyklos* (= *circle*), due to the uniformity it imposes on the overlay.

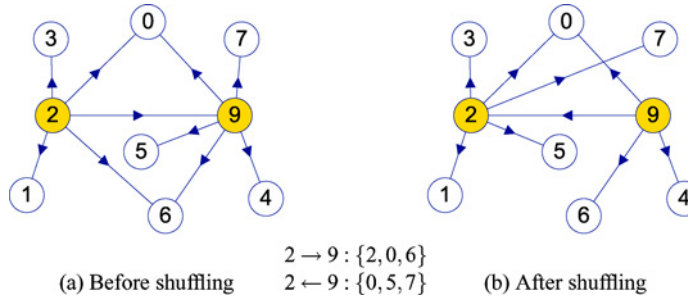


Fig. 1. An example of shuffling between nodes 2 and 9. Note that, among other changes, the link between 2 and 9 reverses direction.

epidemic algorithm. The protocol is extremely simple: each peer knows a small, continuously changing set of other peers, called its *neighbors*, and occasionally contacts a random one to exchange some of their neighbors.

More formally, each peer maintains a neighbor list in a small, fixed-sized cache of c entries (with typical value 20, 50, or 100). A cache entry contains the network address (i.e., IP address and port) of another peer in the overlay. Each peer P repeatedly initiates a neighbor exchange operation, known as *shuffle*, by executing the following six steps:

1. Select a random subset of ℓ neighbors ($1 \leq \ell \leq c$) from P's own cache, and a random peer, Q, within this subset, where ℓ is a system parameter, called *shuffle length*.
2. Replace Q's address with P's address.
3. Send the updated subset to Q.
4. Receive from Q a subset of no more than ℓ of Q's neighbors.
5. Discard entries pointing to P, and entries that are already in P's cache.
6. Update P's cache to include *all* remaining entries, by *firstly* using empty cache slots (if any), and *secondly* replacing entries among the ones originally sent to Q.

On reception of a shuffling request, peer Q randomly selects a subset of its own neighbors, of size no more than t, sends it to the initiating node, and executes steps 5 and 6 to update its own cache accordingly.

Figure 1 presents a schematic example of the basic shuffling operation.

2.2. Enhanced Shuffling

CYCLON employs an enhanced version of shuffling, that, as we shall show in subsequent sections, among other things improves the quality of the overlay

in terms of randomness. Enhanced shuffling follows the same model as basic shuffling. The key difference is that nodes do not *randomly* choose which neighbor to shuffle caches with. Instead, they select the neighbor whose information was the earliest one to have been injected in the network.

The first motivation behind this enhancement is to limit the time a pointer can be passed around until it is chosen by some node for a cache exchange. As we shall see in Section 5, this results in a more up-to-date overlay at any given moment, as it prevents pointers to dead nodes from lingering around indefinitely.

The second—and far less obvious—motivation is to impose a predictable lifetime on each pointer, in order to control the number of existing pointers to a given node at any time. In Section 3.3 we will show that as a consequence of that, pointers are distributed in a remarkably even way across all nodes.

In enhanced shuffling nodes initiate neighbor exchanges periodically, yet not synchronized, at a fixed period ΔT. In addition to the network address, cache entries contain an extra field called *age*, which denotes roughly the age of the entry expressed in ΔT intervals since the moment it was created by the node it points at.

The enhanced shuffling operation is performed by letting the initiating peer P execute the following seven steps:

1. Increase by one the age of all neighbors.
2. Select neighbor Q with the highest age among all neighbors, and $\ell - 1$ other random neighbors.
3. Replace Q's entry with a new entry of age 0 and with P's address.
4. Send the updated subset to peer Q.
5. Receive from Q a subset of no more that i of its own entries.
6. Discard entries pointing at P and entries already contained in P's cache.
7. Update P's cache to include *all* remaining entries, by *firstly* using empty cache slots (if any), and *secondly* replacing entries among the ones sent to Q.

Like in basic shuffling, the receiving node Q replies by sending back a random subset of at most ℓ of its neighbors, and updates its own cache to accommodate all received entries. It does not increase, though, any entry's age until its own turn comes to initiate a shuffle.

From now on, any references to *shuffling* apply to *both* basic and enhanced shuffling. Otherwise, the shuffling type will be explicitly specified.

Note that after node P has initiated a shuffling operation with its neighbor Q, P becomes Q's neighbor, while Q is no longer a neighbor of P. That is, the neighbor relation between P and Q reverses direction.

3. BASIC PROPERTIES

In this section we show and analyze the basic properties of the basic and enhanced shuffling epidemic protocols. All experiments presented have been carried out with an event-driven simulator we developed in C++.

3.1. Connectivity

The fundamental property of shuffling is that, given a fail-free environment, connectivity of the overlay is guaranteed.

Considering the trivial case of *individual* nodes' connectivity, it should be clear that no node becomes disconnected as a result of a shuffling operation. It simply moves from being the neighbor of one node to being the neighbor of another. This provides an intuitive indication that connectivity is generally preserved.

To provide a complete proof, we now show that an overlay cannot be split in two *disjoint* subsets as a result of a shuffling operation. Assume two subsets A and B connected by at least one link. For instance, some node in A has a pointer to some node in B. Shuffles within subset A may pass this pointer around, but it will always point at the same node in B, keeping the two subsets connected. Shuffles within subset B do not interfere with this link. Finally, a shuffle between the node in A currently holding the pointer, and the node in B being pointed at, will simply reverse the direction of the pointer, thus maintaining the link between the two subsets. Therefore, no shuffling operation can result in A and B (or generally any two subsets of the overlay) becoming disconnected.

3.2. Convergence

As it turns out, shuffling has some desirable statistical properties. In order to observe the characteristics of the overlay, we need to consider the connectivity graph, that is, the graph having the peers as vertices, and the links between them as (directed) edges. We consider the undirected version of the connectivity graph, which is taken by simply dropping the direction of the edges. The motivation behind this is that we are interested rather in the "can-communicate" than the "knows-about" version of the graph. A node has the same potential to communicate with another node either if the first is a neighbor of the second or vice versa.

The *shortest path* length between nodes P and Q is the minimum number of edges needed to traverse to reach Q from P. The *average path length* is the average of the shortest path lengths between any two nodes. The average path length is a metric of the number of hops (and hence, communication costs and time) to reach nodes from a given source. A small average path length is therefore essential for broadcasting or, generally, information dissemination applications.

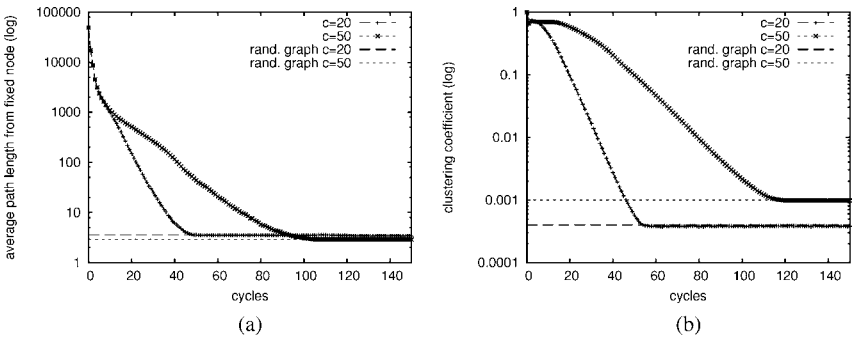


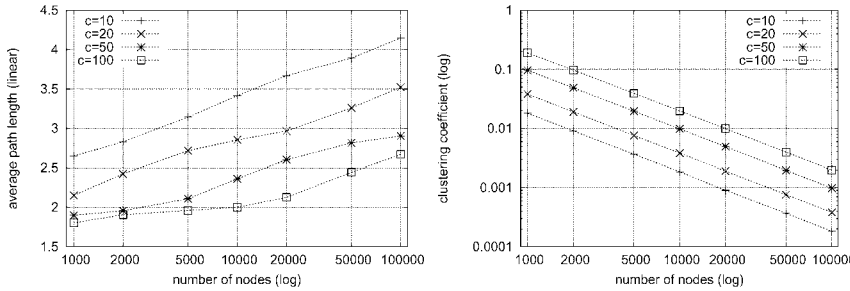
Fig. 2. (a) Average shortest path length between two nodes for different cache sizes. (b) Average clustering coefficient taken over all nodes.

We conducted a series of experiments involving networks containing up to 100,000 nodes. To study the emergent behavior of the protocol, we define a *cycle* to be the time period during which a number of shuffle operations equal to the number of nodes have been made. Since nodes initiate shuffle operations periodically, at the same rate, a cycle coincides with the shuffle period ΔT. Note that during a cycle, each node has initiated a shuffling operation exactly once. We studied the protocol's emergent behavior by observing its state at times 0, ΔT, $2\Delta T$, etc.

Note that the selection of the period ΔT effectively regulates the speed at which an experiment runs in real time. However, it does not affect the protocol's emergent behavior or its convergence speed with respect to the number of cycles elapsed. Nevertheless, ΔT should not be comparably short to twice the typical latencies in the underlying network, as network delays would unpredictably affect the order in which events are taking place. Typical values of $\Delta T = 10$ s or higher are recommended for experiments running over a wide-area network.

Figure 2(a) demonstrates a significant aspect of the emergent behavior of shuffling. It clearly shows that the average path length converges to a very small value, which coincides with the average path length of a random graph with the same number of edges.

The *clustering coefficient* of a node is defined as the ratio of the existing links among the node's neighbors over the total number of possible links among them. It basically shows to what percentage the neighbors of a node are also neighbors among themselves. The *average clustering coefficient* is the clustering coefficient averaged across all nodes in the network. It is generally undesirable for an overlay to have a high average clustering coefficient for two reasons. First, it weakens the connectivity of a cluster to the rest of the network, therefore, increasing the chances of partitioning. Second, it is not optimal for information dissemination



(a) (b)

Fig. 3. (a) Average shortest path length between two nodes for different cache sizes. (b) Average clustering coefficient taken over all nodes.

applications due to the high number of redundant message deliveries within highly clustered node communities.

Figure 2(b) shows that shuffling exhibits convergent behavior for the clustering coefficient. In our experiments, the clustering coefficient always converged to values practically equal to the clustering coefficient of random graphs. Moreover, both the average path length and the clustering coefficient converge almost exponentially (linearly in the log-linear graph).

Note that these experiments ran for several thousand cycles. However, only the initial cycles are depicted, as the values remained stable for all the subsequent cycles, indicating convergent behavior. Also note that we carried out experiments bootstrapped in various different ways, but they all converged to the exact same values. The experiments presented in Figure 2 were—intentionally—bootstrapped with the worst imaginable setting. Nodes were set to form a "chain," each node having a single neighbor, namely its previous one. This way, the average path length was initially the longest possible (i.e., 99,999 hops were needed to reach the first from the last one).

Figure 3 shows the converged values for the average path length and the clustering coefficient, for overlays of different numbers of nodes and cache sizes. Two initial observations can be made. First, the average path length increases logarithmically as a function of the number of nodes in the overlay. Second, the clustering coefficient drops exponentially (linearly in the log–log graph) as a function of the number of nodes.

What is more interesting is that both the average path length and the clustering coefficient converge to the exact values expected in a random graph of the same number of nodes and links. A random graph is a graph where an edge between two random nodes exists with a probability p. Consequently, p is equal to the ratio of existing links among nodes, over the total number of node pairs (total number of *possible* links). Also, in random graphs, the average clustering coefficient, C_{rand},

is equal to p. Therefore, it follows that

$$C_{\text{rand}} = p = \frac{\text{no. of links}}{\text{total no. of possible links}} = \frac{\text{no. of links}}{\frac{N \times (N-1)}{2}} \tag{1}$$

where N is the number of nodes. For the sake of comparison, we consider random graphs with an equal number of links as in our graphs. In our overlay, the number of links is $N \times c$, where c is the cache size. By substituting that in (1), we get:

$$C_{\text{rand}} = \frac{2 \times c}{N-1} \tag{2}$$

One can observe that formula 2, which gives the clustering coefficient for random graphs of the same number of nodes and edges as ours, also provides the exact values retrieved through experimentation in 3(b). This proves that the overlays formed by shuffling have the same clustering coefficient as equivalent random graphs.

3.3. Degree Distribution

The *degree* of a node is the number of links it has to other nodes, in the undirected connection graph. The interest in the degree distribution stems from three reasons. First, the degree distribution is highly related to the robustness of the overlay in the presence of failures as it shows the existence of weakly connected nodes and massively connected hubs. Second, it is an indication of the way epidemics are spread. Third, it provides an indication of how fairly links are distributed among nodes, and, as a consequence, an indication of the distribution of resource usage (processing, bandwidth) across nodes. For the sake of robustness, efficient information dissemination, and load balancing, it is desirable to have a balanced, uniform distribution of links across all nodes of the overlay. In other words, it is desirable to have a degree distribution with low standard deviation.

In the directed version of the connection graph, we distinguish between the *out-degree*, and the *in-degree* of a node, which are the number of edges leaving from and ending at the node respectively. In our case, the out-degree of every node is fixed, and equal to the cache size. Therefore, we concentrate on observing the *in-degree distribution* of our overlays.

Figure 4 shows the in-degree distribution for both basic and enhanced shuffling for two different cache sizes. The in-degree distribution of an overlay with c randomly chosen outgoing links per node is shown as well for comparison. In both protocols, the in-degree distributions demonstrate a peak at the in-degree equal to the cache size, while the number of nodes having larger or smaller in-degrees drops symmetrically according to the shift from the cache size.

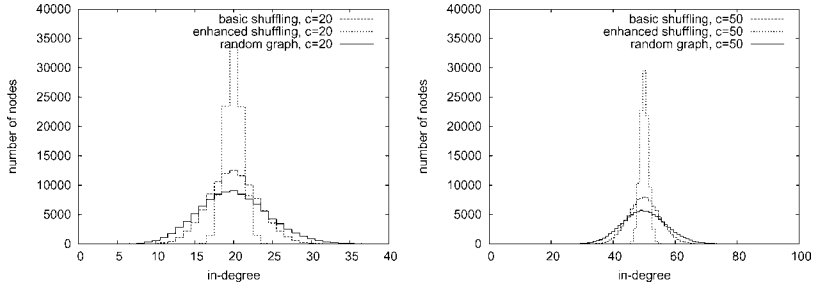


Fig. 4. In-degree distribution in converged 100,000 node overlay, for basic shuffling, enhanced shuffling, and an overlay where each node has c randomly chosen outgoing links.

It is, however, clear that enhanced shuffling does a significantly better job with respect to spreading out the links extremely evenly across all nodes. For the experiment with cache size 20, 80.31% of the nodes have an in-degree of $20 \pm 5\%$. For the experiment with cache size 50, 93.95% of the nodes have an in-degree of $50 \pm 5\%$. The respective percentages for basic shuffling are 36.22 and 38.47%.

To understand CYCLON's enhancement with respect to the in-degree distribution, we should take a closer look at the life cycle of pointers. A pointer to node P is *born* when P initiates a shuffle with one of its neighbors, say Q. In the absence of failures, this pointer will remain in the network, possibly hopping from node to node as a result of subsequent shuffles. It will *die* only when it is selected by the node currently holding it, say R, to perform a shuffle with P, in which case it will be replaced by a fresh pointer from P to R.

In both basic and enhanced shuffling exactly *one* new pointer to each node is born in each cycle, since each node initiates exactly one shuffle. However, the two protocols differ in the *death rate* of pointers.

In basic shuffling, any number of existing pointers to a given node can die in a single cycle, as they are selected for shuffling *at random*. As the death rate does not follow the birth rate closely, the distribution of the *population* of pointers to individual nodes has a high standard deviation, resulting in the wide distribution of Fig. 4.

In enhanced shuffling, in each cycle a node P is contacted by one other node on average to do shuffling, thus inserting one new pointer of age 0 in its cache, and pushing out of its cache the pointer of maximum age. In the subsequent cycle, that pointer of age 0 is upgraded to age 1, and a new pointer with age 0 replaces the currently oldest pointer. As a result, a node's cache contains on average one pointer of each age, from 0 to $c - 1$. This means that replaced pointers are typically of age around $c - 1$. In other words, a pointer has a lifetime of about c cycles. Taking this observation one step further, in each cycle *one* pointer to a given node will die, the one injected by that node c cycles ago. So, the death rate of pointers to a given node is very close to one per cycle, that is, very close to the birth rate,

keeping the population of pointers to that node almost static. This intuitive result can be clearly seen in the distribution of Fig. 4.

3.4. Dependency on Shuffle Length

We conducted a series of experiments to examine the effect of the shuffle length on convergence. Interestingly, for all overlays we tried, the converged state with respect to the average path length, average clustering coefficient, and in-degree distribution, proved to be *independent* of the shuffle length used. The only effect of the shuffle length was in the number of cycles it took to reach the converged state.

We used the in-degree distribution as a metric to identify at which cycle an overlay converges. As the in-degree distribution does not converge to *exact* numbers, but to a certain graph shape whose points keep fluctuating slightly, we had to use an approximation algorithm to identify the convergence point. In particular, we calculated the in-degree distributions for the first 1000 cycles of each experiment. In all cases, by looking at the distribution series we could tell that they were certainly converged well before the 900th cycle. We computed the average in-degree distribution of the last 100 cycles, namely cycles 900–999. Subsequently, for each cycle $i = 900 \ldots 999$ we computed the *sum of squared errors*,[4] E_i^2, between this cycle's in-degree distribution and the average one, and we figured out the maximum, $E^2_{\max(900,\ldots,999)}$. This was used as the maximum threshold of the sum of squared errors to consider a distribution converged. Finally, starting from cycle 0, we checked one distribution at a time to find the first cycle i whose E^2 was below that threshold. This cycle was logged as the cycle for which this experiment converged.

To demonstrate the shuffle length's effect independently of the initial condition, two different bootstrapping methods were used. The first one, *chain*, is the one described in Section 3.2: considering nodes in a line, each node has a single link to its previous one, forming a chain topology. In the second bootstrapping method, *star*, all nodes initially have a single neighbor, the same one for all of them, essentially forming a star topology.

Figure 5 presents the number of cycles an experiment took to converge as a function of the shuffle length, for 100,000 nodes, and cache sizes 20 and 50. In all cases, shuffling just one neighbor at a time took clearly the longest. Shuffling two, three, or more neighbors, gradually sped up the process. However, no significant improvement was noticed beyond shuffle lengths of about 8 or 10. Counter intuitively, convergence speed degraded suddenly when shuffling the whole cache, or almost all of it. The reason behind slow convergence either when

[4] $E_i^2 = \sum_{k=0}^{\infty} (x_{ik} - \bar{x}_k)^2$, where $X_i = \{x_{i0}, x_{i1}, x_{i2}, \ldots\}$ is the i-cycle distribution, and $X_i = \{\bar{x}_0, \bar{x}_1, \bar{x}_2, \ldots\}$ is the average distribution.

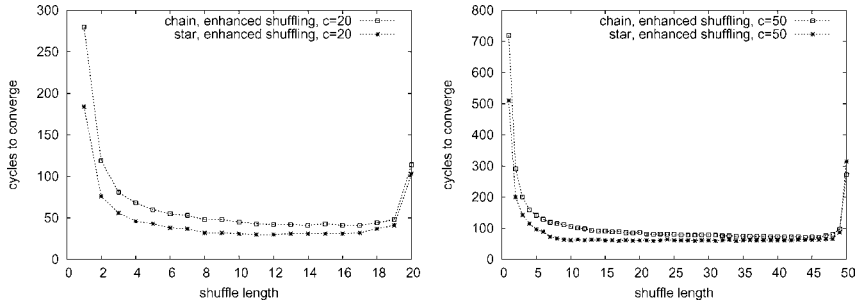


Fig. 5. Effect of shuffle length on convergence speed. $N = 100{,}000$.

shuffling *too few* or too *many* neighbors is that in either case caches are not mixed up too much by each shuffling operation. Therefore, a cache is only minimally (if at all) enriched with new links, even if it has moved as a whole to a new node in the case of full cache shuffling.

This result has more significance when bandwidth is an issue, since the shuffle length linearly affects the amount of bandwidth used by CYCLON. Choosing a shuffle length as low as around six or eight results in nearly optimal convergence speed, while keeping bandwidth utilization to relatively low levels. We return to this issue in Section 7.

4. ADDING NODES

CYCLON introduces a new method for nodes to join the overlay efficiently, without disrupting randomness. To join, a new node simply needs to know any single node that is already part of the overlay, called its *introducer.* Such a node can be discovered in various ways, including broadcasting in the local network, making use of a designated multicast group, or even contacting a well-known server, etc. Finding such an introducer is out of the scope of this paper. Here, we are interested in how to join once an introducer is known, without affecting the basic properties of the system.

To this end, a key observation is that due to the randomness of the connectivity graph, a random walk of length at least equal to the average path length is guaranteed to end at a *random* node of the overlay, irrespectively of the starting node.

Based on this observation, a new node P can join in a fairly straightforward manner. P's introducer initiates c (cache size) random walks, setting their time to live (TTL) to a small value close to the expected average path length, such as four or five. A node Q, where a random walk ends, replaces one of its cache's entries with a new entry of age 0 and the address of P. Q then forwards the replaced cache

entry to P, who, in turn, has to include the entry in one of its cache's empty slots. In effect, this operation is equivalent to P initiating a shuffle of length 1 with a nonadjacent node, namely Q. The join operation ends when all c random walks have ended and the corresponding neighbor exchanges have been accomplished.

We claim that this join operation makes it impossible for an external observer to distinguish P as being different from the rest of the nodes, or to discover any randomness disruption in the overlay. First, P's cache is filled up with c *randomly chosen* neighbors, which renders the values of P's average path length to reach any other node as well as its clustering coefficient, indistinguishable from the respective values of other, older nodes. Second, since there are c random nodes in the overlay that know P, P's in-degree is equal to the cache size. Third, no other node's in-degree has been modified.

In the presence of node failures or an unreliable network, some of the random walks may fail. Note, however, that a node's join does not depend on the complete execution of this join procedure. We ran experiments (not presented here) that showed that a node can join by simply being involved in a shuffle with a single participating node. In that case, though, it will take a few cycles until the new node's properties become indistinguishable from the respective properties of other nodes. The join procedure described earlier in the paper is meant as a means of efficient node joining at a cost of a constant number of messages.

5. REMOVING NODES

In a dynamically changing overlay, nodes may leave for various reasons and in various ways. We make no distinction between nodes disconnecting gracefully or abruptly. What we are interested in is that, once a node disconnects, other nodes should detect it and remove any pointers to it in a timely manner. We consider pointers to disconnected nodes to consist a sort of cache *pollution,* as they take up slots that could be otherwise holding valid, useful links. Particularly in highly dynamic environments, timely elimination of dead links is crucial for the robustness of the overlay.

In order to keep the protocol simple and inexpensive, we do not add any explicit messages (such as frequent pings) to detect disconnected nodes. Instead, CYCLON uses a transparent dead-link detection mechanism, based on the default shuffling message exchange. We do, however, employ an effective strategy (by means of the *age* field introduced in enhanced shuffling) to improve timely detection of disconnected nodes "for free," as a natural consequence of the emergent behavior of enhanced shuffling.

When a node tries to initiate a shuffle with a neighbor and gets no reply within a predefined timeout, it simply assumes that neighbor to be disconnected and removes the corresponding entry from its cache. This way, dead links are gradually being removed. Note that the timeout should be at least twice the

maximum typical latency in the underlying network. For simplicity, a timeout equal to the shuffle period ΔT would suffice.

In the case of basic shuffling, the detection of dead links relies on chance and takes unbounded time. In CYCLON's enhanced shuffling, though, the age field defines a key priority in which neighbors are contacted. A fresh entry (one that has low age), and therefore an entry of a node more probable to be still alive, is less likely to be chosen for shuffling. In contrast, an entry that has been injected in the network several cycles ago (and has since been hopping around between nodes due to shuffles), is more likely to be the oldest one in the cache currently holding it, and therefore more likely to be selected for shuffling. In general, the longer an entry stays in the network, the higher the chances it is selected for shuffling. When P initiates a shuffle and selects an entry with, say, Q's address, that entry is then replaced by a new entry with P's address and age 0. This process naturally recycles the entries, maintaining an equilibrium with respect to their ages, consequently limiting the lifetime of an entry. This way, it is no longer possible for old entries of disconnected nodes to linger around indefinitely.

To demonstrate the advantages of CYCLON's enhanced shuffling with respect to node removal, we ran experiments where we suddenly killed half of the nodes after the overlay had converged. As we shall show in the next section, such a drastic change poses no threat to the (remaining) overlay's connectivity. We observed how long it took for the remaining nodes to "forget" the dead ones. Figure 6 shows the respective graphs for the experiment with 100,000 nodes, out of which 50,000 were killed at once. Figure 6(a) shows how long dead nodes are still referenced, while Figure 6(b) shows the number of dead links that are maintained since the nodes were killed. It is clear that enhanced shuffling limits the detection of dead nodes to a number of cycles equal to (in fact, less than) the cache size, while basic shuffling takes almost an order of magnitude more cycles to decontaminate the surviving nodes' caches.

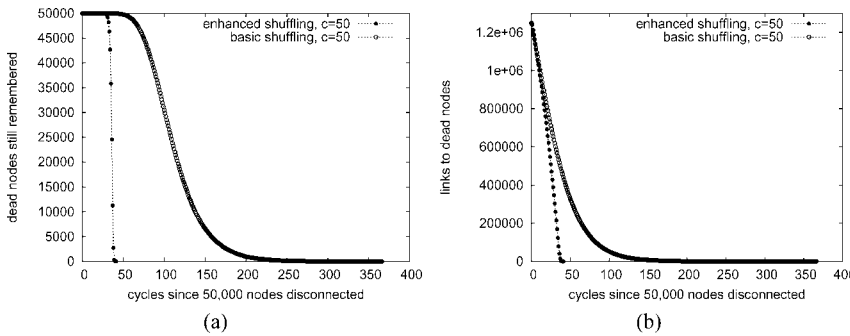


Fig. 6. (a) Time until dead nodes are forgotten. (b) Number of dead links.

6. ROBUSTNESS—SELF-HEALING BEHAVIOR

In the previous section, we dealt with node disconnections, and we mentioned that killing half of the nodes at once does not threaten the connectivity of the remaining ones. In this section, we explore CYCLON's limits in terms of robustness to node disconnections. Shuffling proves to be a very strong and robust epidemic protocol with respect to keeping an overlay connected. Moreover, it appears to exhibit robustness to node disconnections similar to the one found in random graphs.

We conducted experiments as follows. We used CYCLON to create overlays (until they converged), and subsequently examined how the connectivity is affected by node removals. Figure 7 presents the results for networks with initially 100,000 nodes, and cache sizes 20, 50, and 100, respectively. For the sake of comparison, it also presents the same graphs for overlays of cache size 20 and 50, where the neighbors were randomly chosen among the whole node set. Note that simple shuffling has the same behavior as enhanced shuffling with respect to robustness, and therefore the corresponding graphs are not shown. Figure 7(a) shows the number of disjoint clusters as a function of the percentage of nodes removed. Note that the number of clusters decreases as we approach 100% node removal because the total number of surviving nodes becomes too small. Figure 7(b) shows the number of nodes not belonging to the largest cluster, in log scale.

These graphs show considerable robustness to node failures, especially considering the fact that in the early stages of clustering very few nodes are out of the largest cluster, which indicates that most nodes are still connected in a single

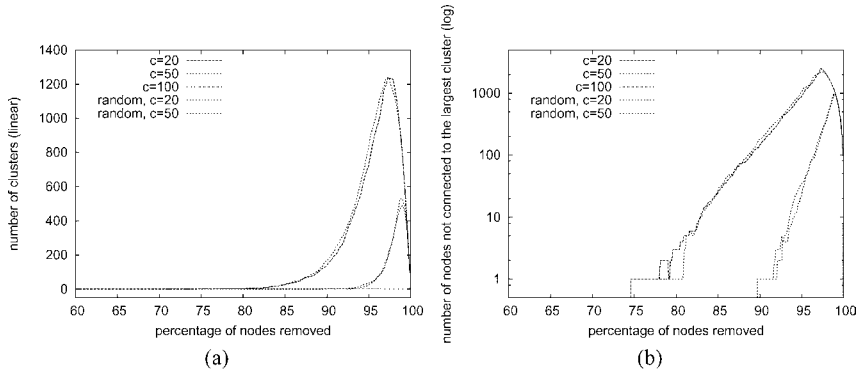


Fig. 7. (a) Number of disjoint clusters, as a result of removing a large percentage of nodes. Shows that the overlay does not break into two or more disjoint clusters, unless a major percentage of the nodes are removed. (b) Number of nodes not belonging to the largest cluster. Shows that in the first steps of clustering only a few nodes are separated from the main cluster, which still connects the grand majority of the nodes.

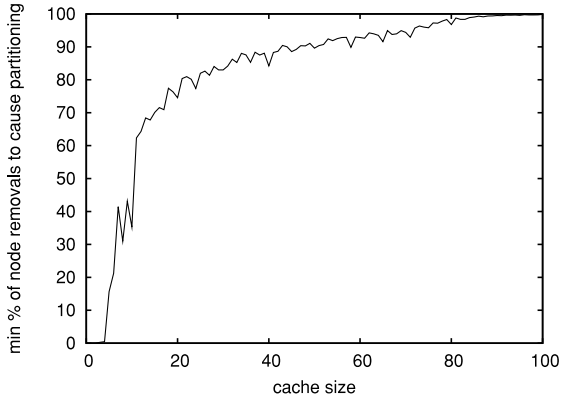


Fig. 8. Tolerance to node removal, as a function of the cache size.

large cluster. Moreover, shuffling appears to share the same robustness properties with overlays where each node's neighbors are a random sample of the nodes in the network.

Note that the graph for the experiment with cache size 100 is practically a flat line. That is, for 100,000 nodes and cache size 100, the overlay created is so robust, that no matter how many nodes are removed, the remaining ones remain connected in a *single* cluster.

The effect of the cache size on the overlay's robustness is shown in Fig. 8. We carried out 100 experiments, with cache sizes $1, 2, \ldots, 100$, and for each of them we determined the percentage of random nodes needed to be removed in order to partition the overlay. It can be seen that there is a critical value of the cache size around 11. Overlays with smaller cache sizes exhibit significantly worse behavior with respect to robustness. On the other hand, overlays with cache size over 85 or 90, are almost impossible to partition, no matter how many nodes are removed.

It is important to point out that the results presented in this and the previous section, suggest that CYCLON is capable of repairing an overlay after a serious disaster, a property often referred to as *self-healing* behavior. This comes as a consequence of the following two facts. First, the overlay has proven to be highly resilient to large-scale node failures. Second, once such a massive failure has occurred, the surviving nodes quickly strengthen the connectivity among themselves by replacing links to dead nodes with valid links in a timely manner.

7. BANDWIDTH CONSIDERATIONS

Due to the periodic behavior of gossiping, the price of maintaining a robust overlay may inhibit a high usage of network resources (i.e., bandwidth). In the

case of CYCLON, the per-node network load depends on two factors: the amount of data transferred per cycle, and the cycle duration.

In each cycle, a node gossips on average twice: exactly once as an initiator and on average once as a responder. It, therefore, on average, sends two gossip messages and receives another two in each cycle. If ℓ is the shuffle length, a gossip message consists of ℓ cache entries. A cache entry is 10 bytes long (IP address: 4 bytes, port: 2 bytes, age: 4 bytes), so, a gossip message is $10 \cdot \ell$ bytes long. Therefore, in each cycle a node experiences total traffic of $40 \cdot \ell$ bytes.

Choosing a shuffle length in the range of 3–8, we achieve nearly optimal convergence speed with respect to the number of cycles (see Fig. 5). The choice of the period ΔT depends on the underlying network's bandwidth availability, as well as on the network's expected churn rate and the application's need for quick convergence. For relatively fast convergence, say, within a few minutes, we could set $\ell = 8$ and $\Delta T = 10$ s. In this case, a node would transfer 320 bytes every 10 s, that is, 32 bytes/s (256 bps). This is very low bandwidth that could be sustained even by modem connections. For less-demanding environments that experience limited churn and failure rate, we could set $\ell = 1$ and $\Delta T = 1$ min, resulting in the negligible bandwidth of 5.3 bps per node.

This analysis backs our claim about CYCLON being inexpensive. Finally, note that all communication is carried out in a connectionless fashion, sending UDP packets.

8. APPLICATIONS

CYCLON is a core technology that can be employed as a building block in P2P applications, particularly in highly dynamic environments. The applications briefly described in this section demonstrate the utility of CYCLON in a range of different contexts.

In our work on semantic-based content searching [8], we use CYCLON as a component in a composite gossiping protocol that establishes links between nodes of similar content in order to enhance searching. In this case, CYCLON serves as a lightweight means of learning *random* nodes of the network. That work can be generalized to grouping nodes based on any proximity metric, such as their domain name, geographical distance, latency distance, etc.

Another potential use of CYCLON is self-monitoring for very large clusters of nodes, possibly in the wide area, avoiding centralized or hierarchical architectures. In such a scheme, each node of a cluster is monitored by some other random nodes of the cluster. The bounded in-degree of nodes ensures that at any given moment, each and every node will be pointed at (and therefore monitored) by a number of other nodes more or less equal to the cache size. This ensures that no node will be left unattended at all.

In [7], the basic shuffling algorithm is employed to construct an overlay that handles flash crowds. On detection of a flash crowd condition with respect to a document request, a client node abandons the respective server, and attempts to retrieve the document in question from peers that have already obtained it. In order to locate the document, the client node performs a series of randomized, scoped searches over the links of the overlay created by basic shuffling.

In [6], we apply a different gossiping protocol, *Newscast* [9, 10], in managing P2P routing tables. In particular, we exploit Newscast's randomized overlay to pick nodes that satisfy certain criteria, to fill in Pastry-like [11] routing tables. CYCLON is, in fact, a better candidate than Newscast in that application, as it exhibits a superior randomness property and lower bandwidth requirements compared to Newscast.

Finally, in Newscast EM [12], Kowalczyk and Vlassis use CYCLON for data aggregation, and more specifically as a component of a distributed Expectation-Maximization (EM) algorithm for probabilistic clustering of a set of (geographically) dispersed data. In particular, they conclude that aggregation using CYCLON is performed *faster* than in a fully connected graph. This is due to the bounded in-degree of nodes, which results in each node having an equal influence on the aggregation.

9. RELATED WORK

There are currently several efforts in constructing unstructured overlays that share properties with random graphs. We have already described basic shuffling, introduced in [7], forming the starting point for our own work described in this paper.

Another example is the Scamp protocol [13]. Scamp is reactive, in the sense that cache exchanges take place only when nodes join, leave, or a failure is detected. As it turns out, the protocol exhibits similar properties in comparison to random graphs when considering its capabilities for information dissemination and recovering from massive node failures. However, no thorough analysis has been undertaken to compare the communication graph with random graphs as we did, but it is known that there are important differences (A.-M. Kermarrec, personal communication).

In many unstructured overlays, such as CYCLON, scalability of the network is achieved by maintaining a partial view on the entire network. The construction of the network itself, that is, membership management, is crucial as we have argued in this paper. It is interesting to see that the assumption is sometimes made that the communication graph resulting from a specific membership protocol is random. However, as is shown in [2], there is a large family of membership protocols for unstructured overlays for which this assumption is false. This includes the work on lightweight probabilistic multicasting [14], as well as the Newscast system

[9, 10]. As it turns out, such membership protocols generally lead to small-world graphs, which distinguish themselves from random graphs by a high clustering coefficient. So far, shuffling appears to fall outside the category of small-world networks.

Of course, random graphs may not be the best structure for communication networks. Alternative schemes are described in [15, 16]. In these cases, the requirements of low diameter, resilience to massive node failures, and inexpensive membership management lead to specific graph-construction protocols. We argue that with enhanced shuffling these requirements are all met, and that the resulting communication graphs allow us to adopt the rigorous analysis of random graphs. Moreover, in contrast to, for example [15], there is no need to use a central server.

In this light, it is also interesting to mention the recent work on Phenix for the decentralized construction of low-diameter, scale-free networks [17]. In Phenix, an additional goal is to construct networks that are resilient to massive malicious *attacks*. We have not yet examined this feature for CYCLON, but suspect its good randomness properties will help in also making it attack resilient.

10. CONCLUSIONS AND FUTURE WORK

In this paper we presented CYCLON, a complete framework for inexpensive membership management in very large P2P overlays. CYCLON is highly scalable, very robust, and completely decentralized. Most important is that the resulting communication graphs share important properties with random graphs. Besides the fact that desirable features such as low diameter and robustness are supported, this similarity justifiably opens the possibility to rigorously analyze the networks.

We also conclude that CYCLON is an improvement of the basic shuffling protocol developed by Stavrou et al. [7]. We offer a scalable and inexpensive membership protocol, achieve better node-degree distributions, and significantly lower the pollution of caches concerning stale references to previous members.

In addition to our continued pursuit for new applications of CYCLON, we will also explore potential improvements of the protocol itself. An important next step in our research will be the replacement of the periodic cache exchanges with a reactive exchange protocol, as in Scamp. We envisage that this replacement will lead to a better utilization of network resources, and incur only minimal costs for detecting failed nodes. Another important subject that we will address is taking network proximity into account. The latter will be largely based on our scalable latency estimation service, described in [18].

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