2009 Third IEEE International Conference on Self-Adaptive and Self-Organizing Systems

Myconet: A Fungi-Inspired Model for Superpeer-Based Peer-to-Peer Overlay Topologies

Paul L. Snyder Rachel Greenstadt Giuseppe Valetto
Department of Computer Science
Drexel University
Philadelphia, Pennsylvania, USA {pls29,greenie,valetto}@cs.drexel.edu

***Abstract*—Unstructured peer-to-peer networks can be extremely flexible, but, because of size, complexity, and high variability in peers' capacity and reliability, it is a continuing challenge to build peer-to-peer systems that are resilient to failure and effectively manage their available resources. We present Myconet, an approach to superpeer overlay construction inspired by the sophisticated, robust, root-like structures of fungal hyphae. Myconet models regular peers as biomass, and superpeers as hyphae that attract and concentrate biomass, while maintaining strong inter-connections with one another. Simulations of the Myconet peer-to-peer protocol show promising results in terms of network stabilization, response to catastrophic failure, capacity utilization, and proportion of peers to superpeers, when compared to other unstructured approaches.**

I. Introduction

Peer-to-peer (P2P) networks are highly-decentralized, distributed systems potentially scaling to millions of peers. P2P networks require high levels of self-management and resilience in the face of changing conditions, as central authorization or supervision is impractical or impossible. Overlays impose a topology on top of these often chaotic networks, and act as an enabler for other services (such as search or routing). Overlays may be either structured (as, for example, with deterministically-placed distributed hash tables) or unstructured.

We have developed a biologically-inspired model, called *Myconet*, for the construction of a robust overlay model within unstructured P2P networks with superpeers. The inspiration for this work comes from the root-like structures of fungi, *mycelia*, and the realization that these natural systems display a number of properties that can be used to guide the self-organization of a P2P network topology.

Biologically-inspired metaphors and models have recently been the subject of active research [1], as they potentially enable properties (such as resilience, emergent adapation, and self-organization) that are desirable for large-scale distributed systems. Specifically, fungi-inspired models have been previously proposed as a paradigm for pervasive adaptive systems [2], [3]. In Myconet, we embrace a fungal metaphor to establish and maintain overlay networks in peer-to-peer systems. *Hyphae* are the root-like structures of some species of fungi), and we leverage the robustness and sophistication of natural hyphal structures to derive interconnection strategies between peers and superpeers, the promotion of regular peers to superpeers, and the incremental aggregation of regular peers around superpeers.

Fig. 1. Mycelium growing [5]

This paper describes the Myconet model for overlay network constuction, and reports a set of empirical results obtained from a simulation of that model developed using *PeerSim* [4]. Our results show how Myconet exhibits a set of desirable properties: it spontaneously and quickly achieves high levels of capacity utilization; at the same time, its topology converges towards a nearly optimal proportion of superpeers to regular peers; finally, the network is resilient and recovers quickly in the face of catastrophic network disruption. The Myconet overlay is designed to dynamically maintain a configurable number of links between superpeers to facilitate network tasks. Myconet makes a design choice to slightly underutilize a subset of superpeers in order to maintain greater flexibility and robustness against failure.

We discuss all of these results, and compare them to other works in recent literature that also aim at the construction of robust and efficient superpeer-based overlay topologies. We also report on the engineering lessons that we have learned while developing Myconet and the insights we have gained on the challenges of designing and implementing a biologically-inspired, self-organizing system. We conclude by outlining future directions for this line of research and for Myconet.

II. Background

Superpeer approaches to peer-to-peer overlays attempt to exploit the heterogenous capacities of the participating peers to improve performance for the entire network [6], [7]. Superpeers may take on service roles for other peers, such as

978-0-7695-3794-8/09 $26.00 © 2009 IEEE
DOI 10.1109/SASO.2009.43

indexing files, routing data, or forwarding searches. Connections between superpeers serve to reduce the network diameter and make these services more efficient.

Designing superpeer-based overlay topologies on large-scale P2P networks is difficult, as no global view of the network exists. Further, such networks can be extremely dynamic as peers frequently join and leave (whether by failure or deliberate disconnection), causing "churn". The number of peers needed for a particular network is unlikely to be known in advance, so decentralized protocols that rely only upon local information and actions, while at the same time presenting coherent emergent properties at the global level, are necessary. Myconet develops such a self-organized overlay model by drawing inspiration from some characteristics of fungi.

Fungi are much more than mushrooms and yeast. Many fungi reproduce primarily by vegetative growth; that is, by extending filamentous strands (called *hyphae*) through the soil (or other growth medium) as depicted in Figure 1. These hyphae search for biomass to assimilate, collecting nutrients and water. The hyphae concentrate the biomass and also use it to fuel hyphal growth. The system of hyphae is referred to as a *mycelium*. The mycelium constantly adapts to changing environmental conditions by routing nutrients and biomass to areas of need.

Mycelia have a number of self-organizing properties. Mycelia grow using decentralized, local interactions from which organization emerges, and are able to adjust to changing conditions or damage by dynamically altering hyphal structures. Branching hyphae may join together in a process termed *anastamosis*, resulting in a multiply-interconnected network that is efficient at transporting nutrients, robust to environmental stresses, and self-healing if injured or disrupted.

Myconet is designed based upon the aforementioned hyphal growth patterns, and aims at showing how they match particularly well with the desiderata for unstructured peer-to-peer network, thus introducing a novel application of the fungal metaphor within the domain of distributed self-adaptive systems.

III. Approach

Myconet uses a relatively simple collection of rules and parameters to regulate the growth and maintenance of the overlay, with each peer continually adjusting its state and connections as needed. Our rules are loosely inspired by a fungal metaphor, in which regular peers are regarded as "biomass" and the superpeers as hyphae criss-crossing the network. We examined several cellular automaton-based models of fungi from the biological literature [8], [9], [10], but opted for a more informal, less constraining design that reflects several dynamics of hyphal growth and achieves the desired properties of emergence and self-organization.

Superpeers in Myconet—which we call "hyphal peers" or "hyphae"—dynamically transition between three states in response to changing network conditions. This adaptive multi-level topology is one of the primary contributions of Myconet. The goal of these transitions is to push load towards high-capacity, stable peers, and build interconnections into the

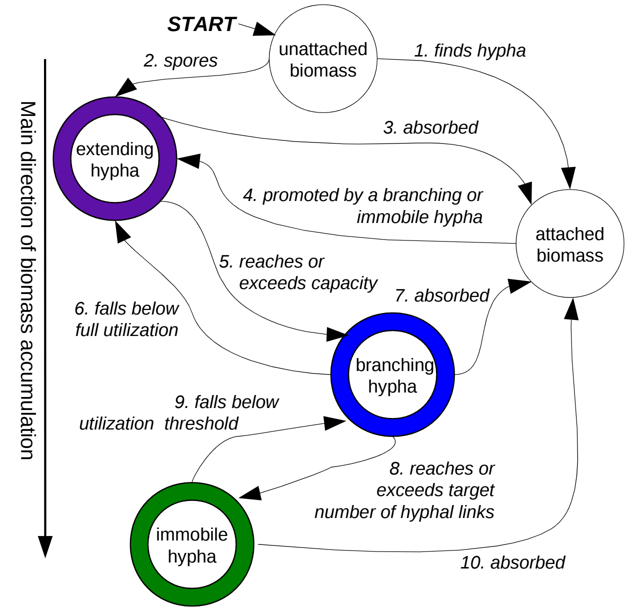

Fig. 2. Myconet protocol state transitions. The transitions are explained by number in Section III. Peers adapatively transition between regular peers (biomass) and three different types of hyphal peers depending on changing conditions.

overlay while maintaining resilience. The state transitions are illustrated in Figure 2 and are explained in detail in the rest of this section. Each hyphal peer maintains a number of links to other hyphal peers, and adjusts the overlay topology according to rules that balance growth or contraction of the overlay with the concentration of biomass around the hyphae best able to make use of it. We refer to the "neighborhood" of a hyphal peer as the collection of biomass peers that are connected to it, and the hyphae to which it maintains hyphal links.

In Myconet, each peer is characterized by a capacity value representing the number of biomass peers that it is able to support. This is a simplification for purposes of simulation, and implementation outside of the simulator will require a more thorough specification of peer quality, in terms of bandwidth, demands of the individual peers, and other relevant attributes. Peers may be temporarily over capacity; in such a case our protocol will shift biomass peers away from overloaded hyphal peers (while possibly promoting other peers to hyphal status, as discussed below).

Hyphal peers can be in different states, depending on their level of biomass concentration (the number of associated biomass peers) and number of hyphal links; the conditions under which a peer transitions between states are shown in Figure 2.

Besides attempting to concentrate biomass peers as close as possible to their capacity, hyphal peers also work towards maintaining a configurable number of connections (C_n) to other hyphal peers, which we call "hyphal links". In general, it is well-known that a strongly interconnected network of superpeers improves the efficiency of certain operations performed over a P2P network, such as search [11], [12], [13]).

Furthermore, it also strengthens the fabric of the overlay in the event of the superpeer failure[14]. In addition to those general benefits, in Myconet hyphal links also provide the means for hyphal peers to exchange biomass peers with one another, driving the overlay towards higher level of utilization of the hyphal peers' capacity. Hyphal links are represented in our system as direct pointers between hyphal peers. In the most of the experiments presented in this paper each hyphal peer attempts to maintain five of these links, that is, $C_n = 5$, but we have also run a set of experiments to examine the effects of varying C_n.

When hyphal peers have achieved C_n interconnections among one another, they will stop creating additional hyphal links unless they again fall below that level. (This may happen because of protocol operations or because a neighbor hypha leaves the network due to churn or failure.)

Bootstrapping of a Myconet network requires a way for peers to discover other live biomass and hyphal peers. We follow the approach used by (among others) SG-1 [15] and use a gossip mechanism to allow peers to acquire information about other peers. PeerSim framework provides a simplified Newscast protocol, which enables each peer to pick randomly another peer, and exchange with it peer lists and state information, that is, whether a peer is *biomass*, *extending*, *branching*, or *immobile*. Myconet leverages this lower-level protocol when it needs to select an arbitrary, non-neighbor hypha.

Biomass Peers

When protocol execution begins, all peers are in the biomass state and there are no hyphal peers. Any single disconnected biomass node b will first try to find a suitable hypha to connect to, by querying the lower-level Newscast protocol (Transition 1 in Figure 2). b will consider only hyphae with available capacity, but it won't otherwise discriminate, choosing randomly in case of multiple possible options. In our current implementation, b attempts to attach to a single hyphal peer. Several works on P2P networks add an additional level of resilience by allowing leaf peers to attach to multiple superpeers (*e.g.*, [14], [7]). Myconet does not currently allows for that, as it rather relies primarily on its protocol rules to achieve robustness in the network topology. Therefore, once the biomass peer b gets attached to a hyphal peer, it takes no other action.

In case no hypha is found, the biomass peer will "spore" (Transition 2 in Figure 2), becoming a stand-alone, extending hyphal peer, which will then be able to attract other neighboring biomass peers, as well as to connect to other hyphae.

Hyphal Peers

Hyphal peers (i.e., Myconet superpeers) may be in one of three states: *extending*, *branching*, or *immobile*.

In accordance with the fungal metaphor, extending hyphae are those that continuously explore the network, foraging for new biomass. (It must be noticed that, as just described, it is actually the biomass peers that seek out an extending hypha and attach themselves to it, but the result is equivalent.) Maintaining some hyphal peers at the extending state at all times allows the network to incorporate new peers into the overlay.

Branching hyphal peers are responsible for growing new extending hyphae and building interconnecting links to other hyphal peers. Immobile hyphal peers are those that are at or near full utilization and have achieved the ideal number of hyphal links (C_n); they pull biomass from branching and extending hyphal peers to keep themselves at full capacity, and regrow hyphal connections whenever they are lost due to churn or failures.

As the protocol continues to execute, the "highest-quality" peers (in our simulation model, those with the highest capacity) will converge towards, and ultimately reach, the immobile state. The protocol guides the overlay toward that goal by using the following general rule: A hyphal peer h always looks for the highest-capacity biomass peer b_{max} that is either a direct client of h, or a client of one of h's neighbor hyphae. If b_{max} has a capacity higher than h itself, then b_{max} and h swap roles: b_{max} becomes a hypha, all of h's biomass peers and links to other hyphae are transferred to b_{max}, and h reverts to being a biomass peer attached to b_{max}. This rule progressively promotes the highest-capacity peers to hyphal peer status.

Hyphal peers then follow further rules depending on their current state: extending, branching, or immobile.

Extending hyphal peers: In the case in which an extending hypha h_e is not connected to any branching or immobile hypha, h_e will attempt to form a hyphal link to a random peer of one of those types (random peers are selected by querying the lower-level Newscast protocol). These links ensure that the initial, stand-alone clusters that form around extending hyphae in the bootstrapping stage of the protocol will gradually converge towards a single, larger connected network.

If no immobile or branching peers can be found, h_e will then try to connect to another extending hypha h_{e2}. Whenever two extending hyphal peers have become neighbors (whether because of this rule or as a result of other protocol dynamics discussed below), the larger will attempt to "absorb" the smaller (Transition 3 in Figure 2), if it has sufficient unutilized capacity. When h_e absorbs h_{e2}, all of h_{e2}'s biomass peers are transferred to h_e, all of h_{e2}'s hyphal links are transferred to h_e, and h_{e2} reverts to being a biomass peer attached to h_e. This rule is the main means by which the number of superpeers in the network is contracted, once again favoring hyphal peers with higher capacity.

Finally, if the extending hypha has reached or exceeded its biomass capacity, it will become a branching hypha (Transition 5 in Figure 2) and the excess capacity will be handled by the rules for branching hyphal peers.

Branching hyphal peers: Branching hyphal peers are at or near their ideal biomass capacity but have yet to reach their ideal number of hyphal connections C_n (see above). Their purpose is multifold: they help to regulate the number of extending hyphal peers in the network, expanding or contracting their number to adequately handle any biomass peers; they act as a conduit to move biomass between extending and immobile hyphae; and they seek to construct new inter-hyphal-peer connections, which are important for the robustness of the overlay.

Branching hyphal peers adjust the number of extending hyphae by attempting to maintain one and only one connected extending hypha. If a branching hypha h_b does not have a link to an extending neighbor (as is the case after it is first promoted to branching status), it will choose its highest-capacity biomass peer and promote it to the extending hypha state (Transition 4 in Figure 2). Branching hyphal peers also help contract the overall number of hyphae in the network: If a branching hypha h_b is connected to two (or more) extending hyphae, it will pick two of them, h_{e1} and h_{e2}, and connect them to each other. h_b maintains its connection to the higher-capacity peer h_{e1}, but severs its connection to h_{e2}. The rules for extending hyphae will then be triggered, leading to the collapse of those two extending hyphal peers in the following round (Transition 3 in Figure 2).

Branching hyphal peers also work to pull biomass from extending hyphal peers; similarly, immobile hyphal peers pull biomass preferentially from branching peers. This way, biomass peers tend to gradually aggregate around those high-capacity hyphal peers that have established themselves in the network over a period of time. Notice that since promotion to branching status occurs only after an extending hypha reaches full utilization, pulling of biomass occurs only when a branching hyphal peer has lost some of its own biomass. That may occur because the biomass has been pulled from them by connected immobile hyphae, or because some biomass peers have left the network.

Whenever a branching hyphal peer has fallen below full utilization, it tries to obtain new biomass from its neighbors. If branching hypha h_b is of larger capacity than a neighbor h_n and h_b's unused capacity is greater than the number of biomass peers attached to h_n, h_b will absorb h_n outright (Transition 7 in Figure 2). All of h_n's biomass peers attach to h_b, all of h_n's hyphal links are transferred to h_b, and h_n becomes a biomass peer of h_b.

If h_b is still not at full capacity after attempting to absorb neighboring hyphae, it then checks whether any of its connected extending hyphal peers have biomass peers; if they do, it will transfer biomass peers to itself until it is at capacity, or until no more biomass is available. In the latter case, if h_b is still under-utilized, it will drop back down to extending status (Transition 6 in Figure 2).

If, as a result of the processes described above, a branching hypha exceeds its capacity (that is, if it has too many connected biomass peers), it will push the excess biomass down to a neighboring extending hypha.

A branching hyphal peer also seeks to reinforce the fabric of the overlay by growing links to other, randomly-selected, existing hyphae: that approximates the process of *anastomosis* in natural fungi. These cross-connections add resilience to the network in case of the failure of one or more hyphal peers. Whenever a branching hypha has accumulated enough hyphal links such that it reaches or exceeds the parameter C_n, it promotes itself to immobile status (Transition 8 in Figure 2).

Immobile hyphal peers: Immobile hyphal peers have achieved their ideal number of hyphal connections and have connected biomass peers sufficient to saturate their capacity. If an immobile hypha falls under its biomass capacity, it will attempt to absorb biomass from a connected branching or extending hypha. In this way, immobile hyphal peers (which not only are high-capacity, but have also proven to be stable by having successfully transitioned through all stages of our protocol) continuously maintain high levels of utilization, and client biomass peers are moved to these peers in preference to other hyphal peers.

If two extending hyphae are connected to an immobile hypha h_i, h_i will create a direct connection between them, so that the lower-capacity hyphal peer is absorbed by the higher-capacity one. (This rule is identical to the rule for branching hyphal peers.) Also, if h_i is connected both to a branching and an extending hyphal peer it will similarly enable the absorption of the extending hypha by the branching hypha.

Next, if an immobile hyphal peer h_i is of larger capacity than a neighbor h_s and h_i's unused capacity is greater than the number of biomass peers attached to h_s, h_i will absorb h_s outright (Transition 10 in Figure 2). All of h_s's biomass peers become attached to h_i, all of h_s's hyphal links are transferred to h_i, and h_s becomes a biomass peer of h_i.

h_i then checks to see if it is still under its biomass capacity. If it is, it will attempt to absorb biomass from neighbor branching or extending hyphae. h_i transfers biomass from such peers until it has reached full utilization or no further biomass peers are available.

If, after this process, h_i is over its biomass capacity, it will transfer the excess to a neighbor with available capacity (immobile, branching, or extending, in order of preference). If h_i does not have any under-capacity neighboring hyphal peers, it will promote its highest-capacity biomass peer to extending status, and transfer the excess capacity to it (Transition 4 in Figure 2).

If h_i drops below the number of hyphal links C_n that Myconet is trying to maintain, whether because any of the rules described above, or because of peers leaving the network, it will randomly form new links to another existing hyphal peer. (As with branching hyphal peers, these are selected from the list maintained by Newscast.) Also, to prevent the topology from becoming stagnant, there is a small probability p that h_i may form another hyphal connection even if it already has C_n neighbor hyphae. (In our simulations, we used $p = 0.05$.)

If, because of any of the above rules (or because other hyphal peers have chosen to connect to it), h_i has more than C_n connections to other hyphae, it will randomly drop extra hyphal connections until it gets back at the C_n level.

Finally, if h_i falls below a certain utilization threshold u_i and is unable to regain the lost biomass, (in our experiments we set the threshhold equal to 80% of h_i's capacity), it will demote itself to become a branching hypha (Transition 9 in Figure 2).

IV. Evaluation

We performed our experiments using a round-based simulation of the Myconet protocol running on top of the Java-based PeerSim platform [4]. We have also leveraged PeerSim for collecting data pertaining to our evaluation, focusing on the following major aspects: 1) how quickly the network self-configures into an overlay with a stable number of hyphal peers; 2) how quickly the overlay reaches certain target levels of utilization of the capacity provided by the set of all peers, that is, how quickly the protocol comes up with a superpeer topology that covers some given percentages of all other peers' capacity; 3) how well the overlay approximates the minimum theoretical number of hyphal peers needed within the network to achieve 100% utilization; 4) the robustness of the overlay, that is, how well it resists and recovers from major disruptions of the network, as in the case of a catastrophic scenario in which a large percentage of the hyphal peers are eliminated. We also examined the effects of varying the ideal number of superpeer interconnections (C_n) that Myconet attempts to maintain.

The above metrics are standard for the evaluation of overlay topologies for unstructured P2P networks. Whenever possible, we not only present our results, but also compare them to those reported in other recent research works with concerns are similar to ours, namely the SG-1 system described by Montresor [6] and the ERASP system described by Liu *et al.* [7]. We have chosen these as our benchmarks since they have reported significant results using one or more of the metrics above and presented them in a consistent way, which makes it possible for us to perform similar experiments within our approach. Whenever feasible, we have configured our environment to match that used by these previous works to facilitate comparison.

In our experiments, the number of immobile peers represents those peers that have established $C_n = 5$ hyphal connections, and the number of branching and extending peers represent peers with less than C_n connections at any given round of our simulations.

The distribution of peer capacities may have significant effects on the behavior of a protocol. We follow SG-1 and ERASP by testing Myconet under two differing capacity distributions. While Liu *et al.* do not specify the exact distributions used in their tests of ERASP, Montresor reports results for SG-1 using (1) a uniform random distribution in the range $[1, c_{max}]$ and (2) a power-law distribution such that the probability of a peer n having a given capacity x are $P[c_n = x] = x^{-\alpha}$, with $1 <= x <= c_{max}$, $c_{max} = 500$, $\alpha = 2$, and a network size of 100,000 peers. [6]. We have used these parameters in our experiments except where noted. The results shown in the Figures in the remainder of this Section represent value averaged over twenty-five experimental runs.

We did note that, though the number of hyphal peers selected by Myconet under the two distributions were slightly different (reflecting the differing capacities available in the network), the shape of the curves for both were extremely similar. We have included graphs for both distributions in Figures 3 and 4, but have chosen to omit the graphs for the uniform distribution for other experiments to avoid redundancy.

To evaluate the ability of Myconet to converge to stable and efficient configuration, we measure the time (i.e., the number of rounds in our simulation) that Myconet takes to converge towards a stable number of hyphal peers. As discussed in the description of our approach, the bootstrapping configuration of Myconet is such that at time 0 all peers can potentially act as hyphae, as they either grow a new extending hypha or find an hypha to connect to.

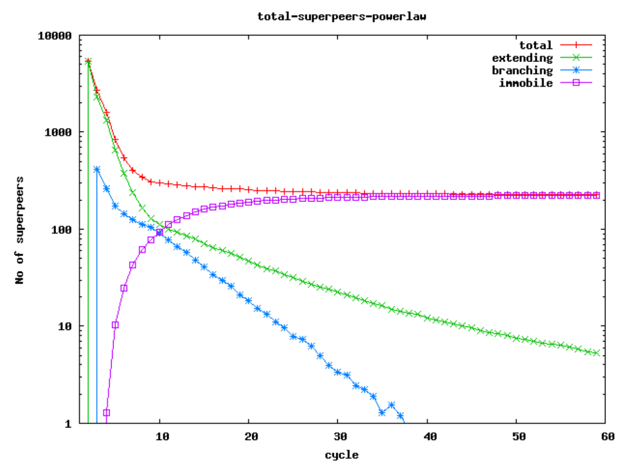

Fig. 3. Hyphal peers in network at each round (power-law). The network quickly converges to around 200 interconnected superpeers.

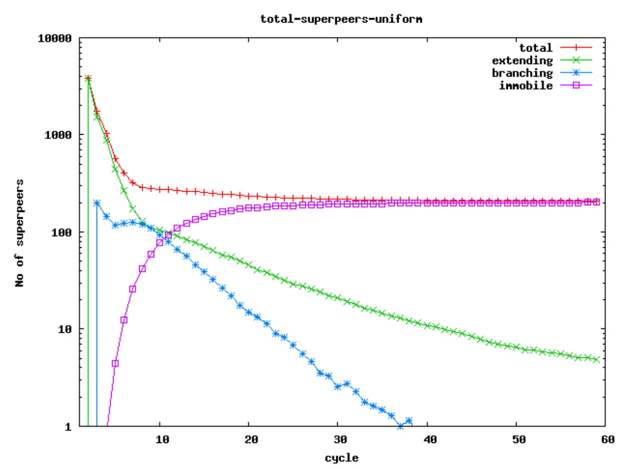

Fig. 4. Hyphal peers in network at each round (uniform). The network quickly converges to around 200 interconnected superpeers.

In Figures 3 and 4, we show the dynamics of the total number of superpeers in a network of 10,000 peers. We also show the number of hyphae in each of the three Myconet protocol stages *extending*, *branching*, and *immobile*. Initially, the number of extending peers spikes very high as the overlay bootstraps. This is followed by a similar, smaller spike in the number of branching peers as the higher-capacity peers are promoted to branching status and absorb their smaller neighbors. Over the next rounds, the largest peers are promoted to become immobile hyphae and the total number of hyphal peers in the network drops as the overlay consolidates biomass peers around those immobile peers.

As no new peers are being introduced into the network in these experiments, the number of branching peers drops to very low levels and the extending hyphae are slowly promoted or absorbed. Peers attached to the remaining extending (and lower-capacity) hyphae are pulled in to become clients of larger and stabler immobile hyphae. Some extending hyphae remain active in the network; this is part of Myconet's continuous quest for further biomass and its adjustment in response to changes in network membership.

Figure 5 shows the utilization trends of the hyphal peers for the power-law distribution (results for the uniform distribution were similar). At the beginning of the simulation, the hyphal peers are designated largely at random and most will be low capacity. The network quickly returns the lower-capacity peers to biomass status and the higher-capacity peers become hyphae (these superpeers will be initially underutilized, as the dip in Figure 5 shows). Then, the overlay escalates branching and immobile peers to full utilization. Looking at the set of all superpeers (including extending hyphae) the overall utilization is somewhat lower, though it quickly climbs into the 80% range and then rises more slowly, as extending peers are promoted or absorbed. This occurs by design, as some underutilized extending hyphae serve as connection points for any loose biomass in the network. When compared with SG-1 and ERASP, the rate of convergence to 80% is similar. Myconet prioritizes quickly reaching capacity of the highest capacity peers while maintaining extending hyphal peers to accomodate growth, so its convergence to 95% utilization is slower, but still occurs by round 30-35. Myconet's slightly lower utilization figures are due primarily to the extending hyphae maintained. As no new peers join the network, the remaining extending peers are slowly reduced, increasing the overall utilization figures.

To compare our approach to a theoretical optimum, we calculate the minimum number of superpeers required for a given network and capacity distribution by repeatedly selecting the largest-capacity peers until the total capacity of the selected peers is equal to or greater than the total number of peers in the network. Figure 6 depicts the number of superpeers selected by Myconet after 60 simulation rounds for network sizes from 10^3 to 10^6, and graphs this against the calculated optimal number of peers (for clarity, only results for the power-law capacity distribution are shown as the curves for the uniform distribution are very similar).

For a network with 1,000 peers (with $c_{max} = 500$ and other parameters as discussed above), on average only 3 superpeers are required to cover all peers, and Myconet converges to that number. Note that the last extending peer will never be promoted as there are insufficient peers in the network to saturate its capacity. Myconet scales smoothly up to 10^6 peers, the largest number with which we tested our simulation. At this network size, the Myconet overlay averaged only 51 peers over the optimum after 60 rounds, which is quite reasonable for a network of one million peers.

To test the self-healing ability of Myconet, we simulated failure conditions by removing large percentages (30% and 50%) of the hyphal peers at round 30 of the simulation. (An equal number of new, unattached peers are introduced at the same time to keep the total number of peers in the simulation at 10^5). As can be seen in Figures 8, 10, 9, and 11, following a catastrophic event the number of hyphal peers spikes while overall utilization drops by roughly the percentage of hyphae killed. The network then quickly reconverges to pre-event

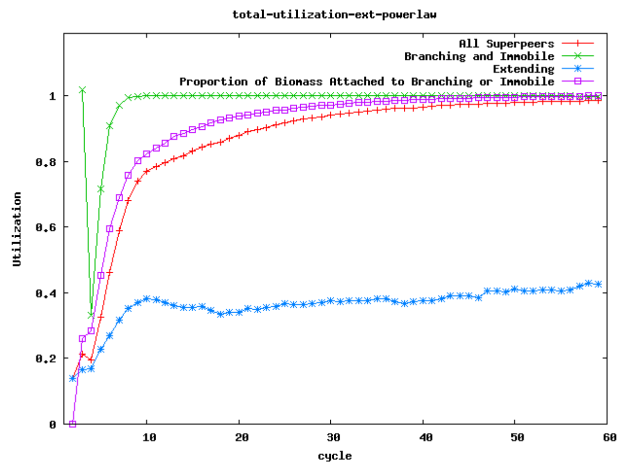

Fig. 5. Superpeer utilization at each round. Branching and immobile peers quickly reach full utilization.

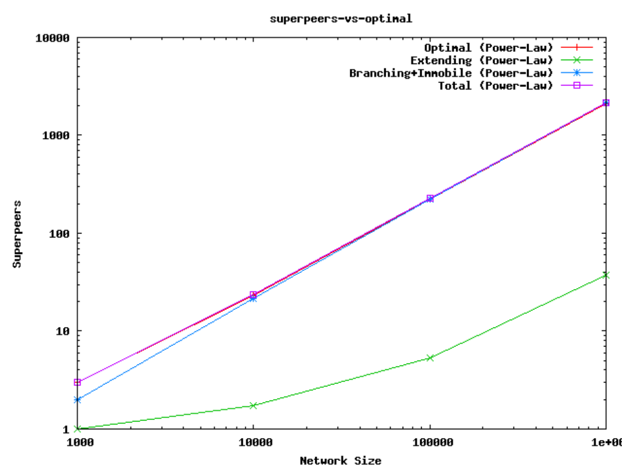

Fig. 6. Hyphal peers (superpeers) in network after 60 rounds vs. theoretical optimum (power-law). The total number of hyphal peers closely tracks the optimum. Results for a uniform capacity network were similar. (Detailed numbers are shown in Figure 7.)

Nodes	Extend	Branching & Immobile	Total	Optimum
10^3	1.00	2.00	3.00	3.00
10^4	1.72	21.64	23.36	22.84
10^5	5.38	221.62	227.00	221.75
10^6	37.44	2134.56	2172.00	2120.88

Fig. 7. Average hyphal peers (superpeers) in network after 60 rounds vs. theoretical optimum (power-law). (This table supplements the graph in Figure 6.)

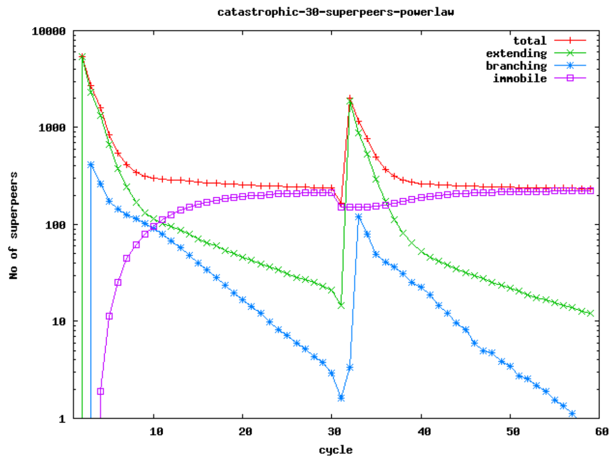

Fig. 8. Number of hyphal peers (superpeers) with removal of 30% of hyphal peers at round 30 (power-law). Following a catastrophic event, the network quickly reconverges to pre-event numbers of superpeers.

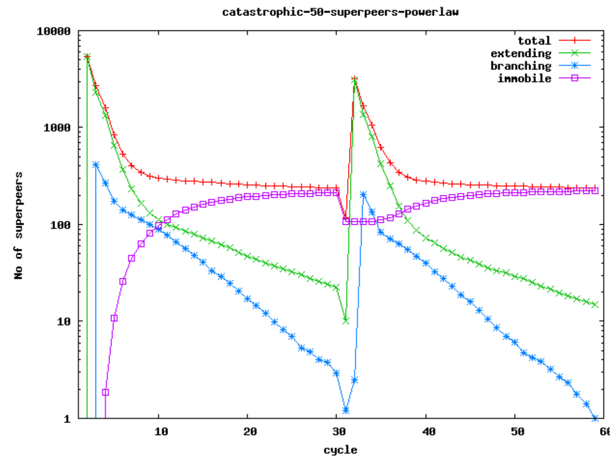

Fig. 10. Number of hyphal peers (superpeers) with removal of 50% of hyphal peers at round 30 (power-law). The spikes are larger when more peers are killed, but the reconvergence rate is similar.

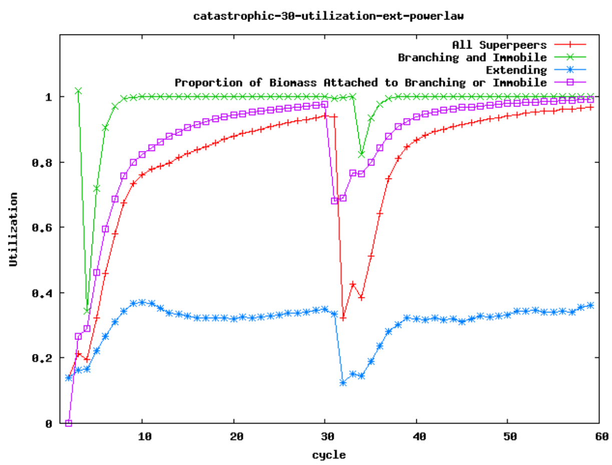

Fig. 9. Utilization with removal of 30% of all hyphal peers at round 30 (power-law). After targeted removal of superpeers, utilization quickly returns to pre-event levels.

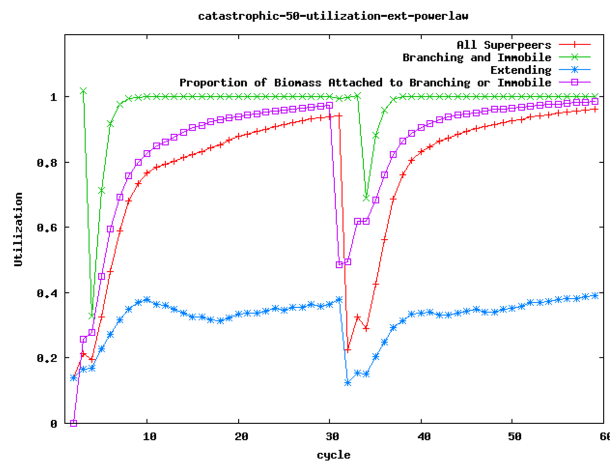

Fig. 11. Utilization with removal of 50% of all superpeers at round 30 (power-law). In the catastrophic scenarios tested, overall utilization immediately drops by roughly the percentage of of peers killed and then ramps back up.

levels. (These figures depict the behavior for a network with a power-law capacity distribution; the behavior for the uniform distribution is similar.)

We also tested the effects of specifically targeting hyphal peers in the *immobile* protocol state. Figures 12 and 13 show the behavior of Myconet when 80% of immobile hyphae are removed at round 30. These peers are replaced by peers whose capacities are randomly drawn from the power law distribution, greatly reducing the available capacity of the peers in the network. While the spikes are somewhat higher in these tests, the network again quickly converges to the new optimum which is still near the pre-event number of hyphal peers and utilization percentages. The reconverged number of hyphal peers is naturally slightly higher, as the killed immobile peers were the highest-capacity peers in the network, and more of the remaining, smaller peers must be promoted to make up the difference.

Our results for these self-healing experiments are particularly interesting when compared to the behavior of our benchmarks, SG-1 and ERASP. The SG-1 paper documents the behavior of the protocol when 50% of the superpeers are killed. For uniform distributions, SG-1 returns to approximately pre-removal numbers of superpeers in ten to fifteen rounds, while the power-law distribution reconverges to a higher number. (Whereas the superpeer count seems to be between 100 and 200 prior to the removal, the network resettles at a number somewhat over 400 superpeers following the event.)

The ERASP paper documents the behavior of the protocol following the removal of 30% of the superpeers for an unspecified capacity distribution. Scenarios are examined in which client peers have either one or two parent superpeers. In the described scenario, the introduction of a second parent

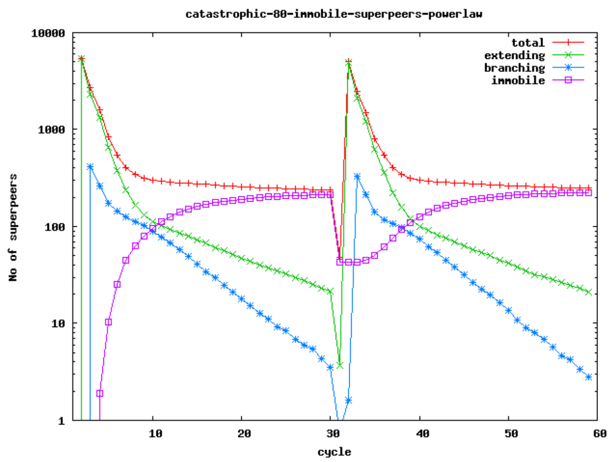

Fig. 12. Number of hyphal peers (superpeers) with removal of 80% of immobile peers at round 30 (power-law). Even when targeting a large proportion of the highest-quality superpeers for removal, the overlay is able to recover quickly.

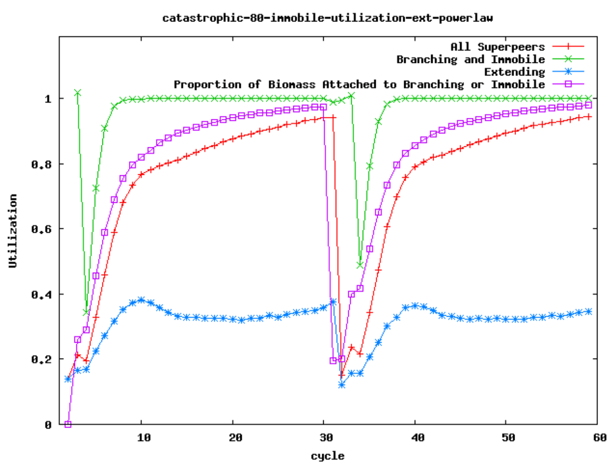

Fig. 13. Utilization with removal of 80% of immobile peers at round 30 (power-law). Myconet recovers well even when large percentages of peers are targeted for removal.

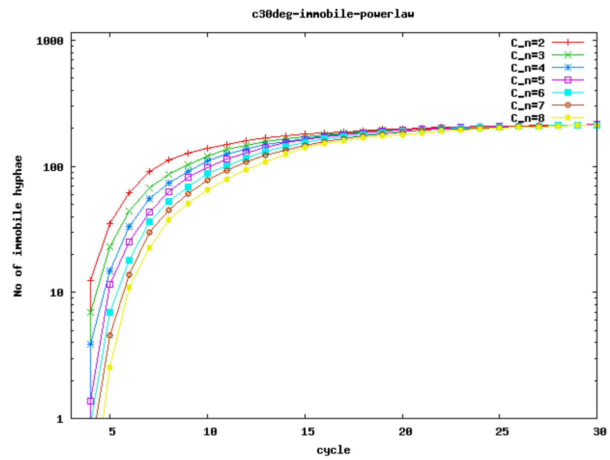

Fig. 14. Number of immobile hyphae in network each round for varying ideal peer degree C_n. Higher values of C_n results in slightly slower promotion of hyphal peers to the immobile state.

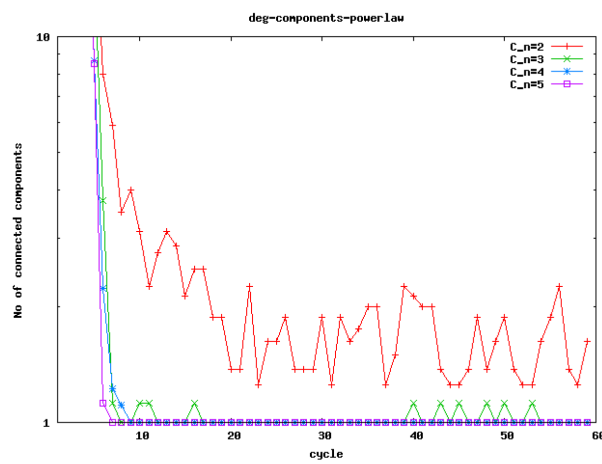

Fig. 15. Conneected components in network each round for varying peer degree C_n. Results for $C_n \geq 6$ are similar to $C_n = 5$. Myconet quickly stabilizes into a single component for $C_n \geq 4$.

superpeer greatly decreases the spike in the number of superpeers immediately following the removal, but, in both cases, the network reconverges to a measurably higher number of superpeers, although it is difficult to determine the quantitative difference from the data provided in the paper.

In contrast, Myconet converges to pre-event levels in all of our experiments. We hypothesize that, in the case of those other systems, the superpeers that survive the catastrophic events might not be significantly re-engaged during the recovery of the overall network, resulting in situtations in which the topology after the catastrophic event becomes less than optimal. In Myconet's recovery process, all types of superpeers participate actively: for example, according to the rules of the protocol, immobile superpeers can be demoted, at least temporarily, or they can be absorbed by superpeers with higher capacity.

To examine the effects of varying the target number of interconnections C_n between hyphal peers, we conducted a series of experiments on 100,000 node networks, varying C_n from 2 to 8. $C_n = 2$ (which in an ideal network would have superpeers connected in a ring topology) was not expected to work well with Myconet's dynamics, but was included for completeness.

We were interested to discover that changing C_n did not noticably affect the total number of hyphal peers in the network, though the rate of promotion of hyphae to the immobile state was slowed as C_n increased (Figure 14).

Also, as shown in Figure 15, Myconet performed poorly with $C_n = 2$, as was expected. Performance with $C_n = 3$ was much better, but the relatively light level of network interconnection resulted in temporary breaks of the network into two or more components. Experiments with $C_n \geq 4$

converged to an overlay with a single component within seven rounds.

V. Lessons Learned

The process of developing and refining the Myconet protocol taught us a number of lessons regarding the idiosyncrasies one can encounter when striving to design emergent behavior in biologically-inspired systems.

Many such systems operate according to simple rules with a concept of locality; that is, elements typically interact only with other elements that are in their immediate "neighborhood". It is well-known that the emergent consequences of a particular local rule at the global level are not always obvious. We experienced this during the development of Myconet, and observed that the behavior of the system could be quite sensitive to small changes in rules or parameters. For example, for the overall behavior and performance of the Myconet protocol, one of the most signficant steps was the addition of the rather simple rule whereby the larger of two connected, extending hyphal peers demotes the smaller one and absorbs all of its biomass peers. This rule proved to be instrumental for the rapid consolidation of hyphal peers, for efficient convergence towards a stable number of hyphal peers, as well as for high levels of capacity utilization.

Sensitivity to small, local changes is coupled with the current lack of a systematic discipline and best practices for testing emergent systems. We felt our trial-and-error process was truly a "Galilean" loop of observation, hypothesis formulation, and experimentation. That highlights the importance of inserting parameterization and modularity in the system, allowing the exploration of a wide range of possible settings, often along multiple design dimensions. This is also where the value of a powerful and flexible simulation tool in the desiger's arsenal becomes most evident.

A further challenge was observing and regulating the behavior of the system at very large scales. While we were able to view the complete behavior of the network and all peer interactions at smaller network sizes, direct observation was not feasible for networks of 10^4 peers or larger. This was crucial because, while in the process of experimenting with and tuning the protocol rules, the emergent behavior of the system could vary significantly at different scales. The most useful tools for working with very large scales were extensive logging and instrumentation, which allowed us to gather detailed statistics, and validate the behavior of the system at both local and global levels.

Besides being prepared to overcome these challenges, a designer of biologically-inspired systems should also be ready to recognize, accept and embrace the "surprises" that the emergent nature of those systems will reveal. In the case of Myconet, although we began with a clear set of objectives, in the end we came to realize that certain design characteristics (which we now regard as significant contributions of the protocol) revealed themselves incrementally during the design process.

A major example is the role of extending hyphae. By continuously growing new extending hyphae, Myconet trades some speed in network convergence for an approach where continual adaptation and adjustment are built-in. The consequence is that we introduce a slight measure of non-determinism in the network configuration: In Myconet, extending hyphal peers are always "on the prowl" for new biomass; the relationships that other types of hyphal peers have with the extending ones ensure they remain open to self-optimization opportunities. As a result, the robustness and ability of the system to self-heal are enhanced, which is instrumental in the ability of our protocol to reconverge to a near-optimal configuration following a catastrophic disruption to the network.

Another example is the way our various hyphal peer types effectively codify in the protocol what in other systems is only a heuristic: that is, the fact that "veteran" peers often make good superpeers. In Myconet, we observed that a peer typically tends to be promoted to immobile status when it has high capacity *and* has participated in the network for enough time. That is not a heuristic, but an intrinsic aspect of how the rules handle peers, by promoting them through the different stages of the protocol.

VI. Related Work

Approaches for peer-to-peer overlay networks are surveyed in [16], which discusses both structured and unstructured models. Many structured approaches exist, such as Chord, Pastry, Tapestry, and Kademlia. As we are focusing on unstructured overlays, we will not delve deeply into this area.

Unstructured approaches include such well-known file-sharing networks as BitTorrent [17], eDonkey [18], KaZaa [19], and Gnutella [20]. Many of these networks employ superpeers to facilitate and/or speed up a variety of critical functionality, such as search of information and routing of data. Because of dynamism and the lack of global structural information, it is often unfeasible to predetermine the topology and the quantity of superpeers that are required to adequately service a P2P network, so adaptive techniques are commonly applied to this problem.

It is also noticeable that several approaches exist that tackle a generalization of this problem, that is, "topology management". Those approaches aim at manipulating generic network topologies (not necessarily, or exclusively, P2P networks) in a self-adaptive or self-organizing way. For instance, Zweig and Zimmerman present an approach that is able to autonomically respond to node failures in a network by switching between a scale-free and a normal or Poisson topology [21]. In [22], local information on neighborhood structure is used to drive the network incrementally closer to a given set of requirements about its overall topology by perturbing the neighborhoods in ways that are consistent with the goals set by those requirements.

A work that aims at topology management specifically in a P2P network is T-MAN [15]. In T-MAN, a gossip protocol is used to diffuse information, and enable the gradual evolution of the network towards a preferred topology, which is defined by means of a ranking function predicated on inter-node distance. T-MAN shows how a structured overlay such as a ring or torus can be efficiently imposed on an unstructured network. SwapLinks [23] also examines overlay construction, but focuses on building random (single-level, non-superpeer) graphs and enabling random node selection.

Although generic topology management approaches could conceivably be used to address the specific issue of creating a superpeer-based overlay in P2P networks, self-organizing approaches that focus upon building a superpeer topology aiming at the nearly-optimal utilization of the collective peers' capacity and network robustness show the closest similarity with Myconet. Among them, the aforementioned SG-1 [6] and ERASP [7], also build and maintain two-level (superpeer) hierarchies; however Myconet's superpeers are further differentiated into extending, branching, and immobile peers. Myconet's overlay differs from both SG-1 and ERASP by introducing mechanisms that adjust the interconnections between superpeers, to reinforce the overlay and achieve self-healing and self-optimization. In contrast, ERASP examines the effects on the overlay of allowing regular "leaf" peers to connect to multiple superpeers. Like Myconet, ERASP uses a concept of the time that a node has participated in the network as a factor in determining its attitude to become a superpeer.

Other published superpeer overlay approaches include [11], which proposes "clusters" of superpeers, where superpeers in each cluster act as parents for the same group of clients and uses a simple splitting method when a superpeer exceeds its capacity. [24] and [25] focus on a separate problem, that of locality in superpeer selection. Those approaches use Yao-Graphs to organize superpeer coverage based on the underlying network topology.

Our work is also related to other fungi-inspired mechanisms that have been previously examined for application to communication problems. At the 2008 PerAda Summer School workshop in Rimini, Paechter *et al.* proposed a biologically-inspired model based on the behavior of fungal colonies. [2]. Their initial work applies a relatively low-level fungal model to routing in a small telecommunications network [3]. Our approach is inspired by fungal models in a looser way, and applies it as a high-level metaphor and a design framework. As we discuss in the following section, our framework can support further refinements, in the direction of formal and detailed representations of fungal behavior and growth.

VII. Conclusions

Myconet demonstrates that the fungal metaphor is powerful when applied to peer-to-peer overlays and that it can be used to create a self-organizing peer-to-peer overlay that provides advantages over other approaches in terms of its robustness to failure. We therefore urge other researchers not to overlook fungi as a source of inspiration for biologically-inspired systems.

The Myconet protocol effectively constructs and maintains a strongly interconnected, decentralized superpeer overlay that scales to at least 10^6 peers. This overlay quickly converges to an optimal number of superpeers and high levels of capacity utilization. Myconet's greatest strength is its ability to self-heal the interconnected overlay, quickly repairing the damage from catastrophic events in which 30-50% of the peers are removed from the network. Even when 80% of the highest capacity, most stable superpeers are removed, Myconet is able to quickly reconfigure its overlay to reflect the new capacity of the network while dynamically adjusting the interconnections between superpeers.

Myconet's results are promising enough to warrant further investigation. In particular, we wish to examine the communications efficiency of the protocol, and the overhead required to maintain the overlay. We also would like to investigate how the Myconet topology affects the performance of peer-to-peer applications run on top of it. Under the current implementation of Myconet's rules, biomass peers are connected to only a single hyphal peer at a time. We plan to explore the effects of multiply-connected biomass peers as part of our future work.

We also want to gain insight on the performance of Myconet under network churn. We have gathered data in the current experimental framework that suggests that Myconet can withstand up to 5% churn at each round. However, it is hard to interpret the significance of these results because of the round-based nature of our simulations. After examining several studies of churn in P2P filesharing networks [26], [27], we have come to the conclusion that an accurate, meaningful evaluation of this aspect will require moving from round-based to continuous simulation, or directly to implementation and live network experimentation.

We are also examining the possibility of exploiting mathematical models of fungal growth developed in the computational biology literature (e.g., [9], [8], [10]). In particular, we would like to explore whether framing Myconet in such a model can enable some level of "a priori" reasoning on the effects of design decisions on the rules and the parameters of the protocol on the behavior and characteristics of our overlay. This would be valuable during the next phases of Myconet's development, especially as we move towards actual system implementation.

References

[1] L. De Castro, *Fundamentals of Natural Computing: Basic Concepts, Algorithms, And Applications*. Chapman & Hall/CRC, 2006.

[2] B. Paechter, E. Hart, and R. Falconer, "Emergent computing for pervasive adaptation," First PerAda Summer School on Pervasive Adaptation, 2008.

[3] R. Falconer, J. Bown, E. Hart, and J. Timmis, "A new paradigm for specknets: Inspiration from fungal colonies," in *Proceedings of the First Perada Workshop on Pervasive Adaptation*, 2008.

[4] M. Jelasity, A. Montresor, G. Jesi, and S. Voulgaris, "PeerSim: A Peer-to-Peer Simulator," *URL: http://peersim. sourceforge. net*.

[5] K. M. Fleming, "mycelium?" (CC-licensed photo from Flickr) http://www.flickr.com/photos/myriorama/101120710/, 2004.

[6] A. Montresor, "A robust protocol for building superpeer overlay topologies," in *Proceedings of the 4th International Conference on Peer-to-Peer Computing*. Zurich, Switzerland: IEEE, Aug. 2004, CONFERENCE, pp. 202–209.

[7] W. Liu, J. Yu, J. Song, X. Lan, and B. Cao, "ERASP: An Efficient and Robust Adaptive Superpeer Overlay Network," *Lecture notes in computer science*, vol. 4976, p. 468, 2008.

[8] G. Boswell, H. Jacobs, K. Ritz, G. Gadd, and F. Davidson, "The Development of Fungal Networks in Complex Environments," *Bulletin of Mathematical Biology*, vol. 69, no. 2, pp. 605–634, 2007.

[9] A. Meškauskas, M. Fricker, and D. Moore, "Simulating colonial growth of fungi with the Neighbour-Sensing model of hyphal growth," *Mycological Research*, vol. 108, no. 11, pp. 1241–1256, 2004.

[10] P. Gerlee and A. Anderson, "Stability analysis of a hybrid cellular automaton model of cell colony growth," *Physical Review E*, vol. 75, no. 5, p. 51911, 2007.

[11] B. Yang and H. Garcia-Molina, "Designing a super-peer network," in *Proceedings of the 19th International Conference on Data Engineering (ICDE)*, 2003, p. 49.
[12] P. Garbacki, D. Epema, and M. Van Steen, "A two-level semantic caching scheme for super-peer networks," in *Web Content Caching and Distribution, 2005. WCW 2005. 10th International Workshop on*, 2005, pp. 47–55.
[13] Y. Yang, R. Dunlap, M. Rexroad, and B. Cooper, "Performance of full text search in structured and unstructured peer-to-peer systems," in *IEEE INFOCOM*. IEEE Press, 2006, pp. 2658–2669.
[14] B. Mitra, F. Peruani, S. Ghose, and N. Ganguly, "Analyzing the vulnerability of superpeer networks against attack," in *Proceedings of the 14th ACM conference on Computer and communications security*. ACM New York, NY, USA, 2007, pp. 225–234.
[15] M. Jelasity and O. Babaoglu, "T-Man: Fast gossip-based construction of large-scale overlay topologies," *University of Bologna, Department of Computer Science, UBLCS-2004-7, Bologna, Italy*.
[16] K. Lua, J. Crowcroft, M. Pias, R. Sharma, and S. Lim, "A survey and comparison of peer-to-peer overlay network schemes," *Communications Surveys & Tutorials, IEEE*, pp. 72–93, 2004.
[17] B. Cohen, "BitTorrent protocol specification," in *First Workshop on Economics of Peer-to-Peer Systems (P2P03)*.
[18] O. Heckmann and A. Bock, "The eDonkey 2000 Protocol," Tech. Rep. KOM-TR-08-2002, Multimedia Communications Lab, Darmstadt University of Technology, Dec. 2002, Tech. Rep.
[19] J. Liang, R. Kumar, and K. Ross, "Understanding KaZaA," *Manuscript, Polytechnic Univ*, 2004.
[20] M. Ripeanu, "Peer-to-Peer Architecture Case Study: Gnutella Network," in *Proceedings of International Conference on Peer-to-peer Computing*, vol. 101. Sweden: IEEE Computer Press, 2001.
[21] K. A. Zweig and K. Zimmermann, "Wanderer between the worlds - self-organized network stability in attack and random failure scenarios," in *Conference on Self-adaptive and Self-organizing Systems (SASO)*, 2008.
[22] V. Matossian and M. Parashar, "Towards autonomic control of network topologies," in *1st IEEE Workshop on Modeling Autonomic Communication Environments (MACE), 2nd International Week on Management of Networks and Services (Manweek 2006)*, 2006.
[23] V. Vishnumurthy and P. Francis, "On Heterogeneous Overlay Construction and Random Node Selection in Unstructured P2P Networks," in *Proc. INFOCOM 2006*, 2006.
[24] M. Kleis, E. Lua, and X. Zhou, "Hierarchical Peer-to-Peer Networks using Lightweight SuperPeer Topologies," in *Proceedings of the 10th IEEE Symposium on Computers and Communications (ISCC 2005)*, 2005, pp. 143–148.
[25] E. Lua and X. Zhou, "Network-aware SuperPeers-Peers Geometric Overlay Network," in *Computer Communications and Networks, 2007. ICCCN 2007. Proceedings of 16th International Conference on*, 2007, pp. 141–148.
[26] Z. Yao, D. Leonard, X. Wang, and D. Loguinov, "Modeling heterogeneous user churn and local resilience of unstructured p2p networks," in *Proc. IEEE ICNP*, 2006, pp. 32–41.
[27] D. Stutzbach and R. Rejaie, "Understanding churn in peer-to-peer networks," in *IMC '06: Proceedings of the 6th ACM SIGCOMM conference on Internet measurement*. New York, NY, USA: ACM, 2006, pp. 189–202.