Filamentous Fungi Growth as Metaphor for Mobile Communication Networks Routing

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Abstract—**Filamentous fungi have a structure called mycelium which is the vegetative part of the organism that forms the body or colony, which can function as a support, reproduction and absorption structure of nutrients and is composed of a tangle of hyphae that can grow without stopping while the fungus finds food and favorable conditions to survive. Inspired by fungi, it is possible to directly equate the structure of the mycelium with that of a communication network, so hyphae can be compared to links, and the tips and derivations of hyphae with nodes of the network. In this context, the growth process of filamentous fungi to explore the environment in which they live can serve as a metaphor for routing algorithms that seek a path between a source and a destination node. Based on this idea, this paper investigates a functional routing algorithm (HyphaNet) for wireless communication networks. Analytical modeling and validation tests proved that HyphaNet converges to more advantageous routes while exploring the search space. Finally, it can deliver good performance on the metrics packet delivery rate, average end-to-end delay and overhead, when compared to other well-known protocols.**

Index Terms—**mobile communication, routing protocols, biological system modeling, learning systems, performance analysis.**

I. Introduction

Currently the use of artificial intelligence (AI) assists in the design of algorithms bioinspired by the collective behavior of social insects and other animal societies. Within AI, there are swarm intelligence (SI) -based systems where, for example, it is found the classic ant colony optimization (ACO) model that is inspired on how ants find food. In this context, there are also other approaches based on nature, such as the artificial bee colony (ABC) that simulates the intelligent behavior of a bee swarm in search of nectar, as well as optimization metaheuristics inspired by the behavior of fireflies (firefly algorithm - FA), bats (bat algorithm - BA), birds (cuckoo search - CS), among others. Most of these natural systems have achieved this behavior after evolving for millions of years [1-4]. Thus, it attracts the interest of researchers for the development of nature-inspired algorithms for efficient solutions to the most diverse problems.

Recently another frontier of nature has been a source of inspiration for the development of new solutions: fungi. Fungi are living organisms that usually feed on decaying matter and live in damp and shady environments, popularly known as mushrooms, molds, yeasts, among others. They grow and expand through hostile regions to discover new resources. Along with bacteria, they are the main decomposers of the planet. Many fungal species form complex filament networks (hyphae), which transport nutrient material, to survive in heterogeneous environments. The vegetative part of the organism that forms the body is known as mycelium. Unlike other biological transport networks, such as plants or vascular systems in animals, the network formed by these organisms is not part of the organism it is the organism itself. These networks develop as the organism expands in an irregular environment looking for new resources. They must transport nutrients between spatially separated production and consumption regions and also maintain the integrity of the network in the face of predation or random damage [5].

In the context of communications, a communication network is a decentralized set of nodes that exchange information temporarily through peer-to-peer transmission using a wired and/or wireless infrastructure. The network topology may or may not be structured; nodes act as terminals and/or routers, and may enter or leave the network freely. This way, a node can communicate with any node within the network, directly with those nearby or through multi-hop routing. Especially in mobile networks, nodes have the characteristic of mobility, so self-organizing mechanisms capable of working with the dynamic nature of the topology, failure recovery and security, as well as heterogeneity, resource constraints and scalability, are required [6-9].

Just as many technologies were inspired by the behavior of social insects, fungi also demonstrate triumphant behavior in the struggle for survival and suggest a complex ability to self-assemble robust, resilient, adaptive control networks and desirable transport mechanisms in various protocols and, especially, in the routing algorithms present in modern communication networks. In this context, the growth process of filamentous fungi to explore the environment in which they live can serve as a metaphor for routing algorithms that seek a path between source and destination nodes. The mycelium can be compared with a communication network, so hyphae can represent links, and the tips and derivations of hyphae are nodes of the network.

This paper is an extension of a recent study [10] that proposes a routing algorithm for wireless networks called HyphaNet. This extension covers, in addition to the protocol presentation itself, the proof of concept, results from new simulations, and mainly the algorithm convergence analysis (which is not covered in the original article).

This paper is organized as follows. In order to have the necessary knowledge about fungi, their morphology, their

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growth process, and their nutrient transport mechanisms are presented and discussed in Section II. Section III presents examples of filamentous fungi-inspired algorithms. The investigation of the functional routing algorithm (HyphaNet) for wireless communication networks is presented in Section IV. This section also presents the convergence analysis of the algorithm, as well as, results of experiments involving network scenarios aiming to validate and test the proposal. Conclusions and future work are presented in Section V.

II. Fungi Colony

A. Definitions and Morphology

Fungi are unicellular or multicellular eukaryotic organisms that have microscopic and macroscopic structures, heterotrophic and facultative aerobic or anaerobic structures (yeast). They belong to the Fungi kingdom according to the classification of Whittaker [11] or to the Eukarya domain proposed by Woese, Kandler and Wheelis [12].

Some fungi exist in the form of yeasts, being unicellular, and others in the form of filaments being pluricellular. The structure that represents the body or the colony of fungi is called fungal mycelium. The mycelium is formed by the set of filaments, called hyphae, which can function as a structure of sustentation, reproduction and absorption of nutrients. The hypha is a kind of filament with a hollow inner tube that is responsible for nutrient transport and fungal growth and is usually a structure that grows with elongation at the extremities [13]. Certain fungi, commonly known as mushrooms, have reproductive structures called fruiting bodies, which are above ground (Fig. 1).

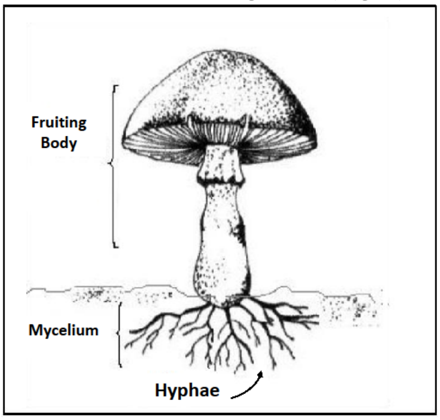

Figure 1. Structure of a mushroom-like fungi.

B. Mycelial Fungi Growth

The growth mechanisms of mycelial fungi can be divided into four main stages: spore germination, hyphal growth, branching and, finally, fungal differentiation, as shown in Fig. 2. After spore germination, a tube (germination tube) extends through tip growth initiating the formation of the hyphae. The hyphae branching process allows the mycelium expansion, ensuring an increase in the surface area of the colony (presumably increases the likelihood of finding and assimilating nutrients). Branches can also cause fusions between hyphae from different sites. Finally, differentiation refers to the process of changing hyphae. For convenience, during colony ripening, vegetative hyphae may change to specialized hyphae for reproduction [14].

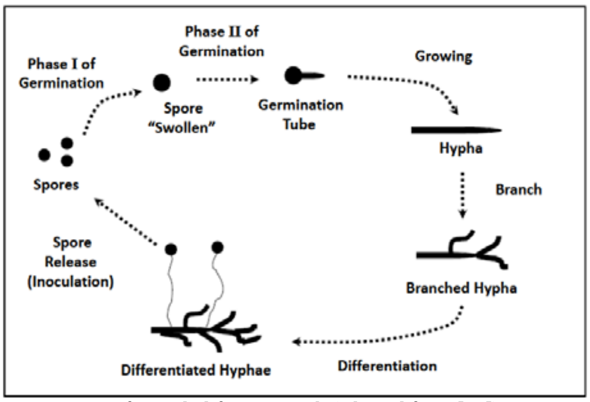

Figure 2. Stages of mycelial fungi growth (adapted from [13])

The fungal mycelium grows as it receives nutrient biomass, in this case it is a combination of two types of biomass: *immobile* and *mobile biomass* [15], as described below:

a) Immobile Biomass – It is the material that constitutes the mycelium and the complex network of tubes inside the hyphae, through which the mobile biomass can flow. Immobile biomass can be in one of two states:

– Non-insulated, which is the biomass associated with hyphae capable of significant absorption of external resources and corresponds mainly to the active hyphae tips within a colony;

– Insulated, which is the biomass of the mycelium present in areas with little or no absorption of nutrients. These are areas of the mycelium basically used for sustentation.

b) Mobile biomass – It is the material that flows through the hyphae's communicating tubes in order to provide nutrients to the mycelium ends. Mobile biomass tends to become immobile biomass when and where it is useful to the organism.

Many types of fungal mycelia exhibit autolysis of older parts of the colony, especially when growing in nutrient-poor environments [14]. Thus, fungal networks progress from a radial branching tree to a grid net (lattice-like) through a process of fusion and reinforcement to selective removal of loops and recycling of the redundant material [16]. Fungal growth is influenced by stimuli from internal (autotropism) and external (tropism) factors. Growing hyphae seem to actively avoid each other, an example of negative autotropism [17].

C. Tero's Experiment

In order to demonstrate the ability of fungi to solve problems Tero et al. performed an experiment on cultivation of slime mold *Physarum polycephalum* to simulate the interconnection of Tokyo railway stations and its metropolitan region [18]. To represent the *P. polycephalum* growth scenario, a smooth wet container was used as a surface and oat flakes were deposited representing the main cities in positions corresponding to the region map. The initial mold was placed in a central position, which would represent the position of Tokyo. To complete the picture, obstacles that could produce changes in direction and speed of growth (e.g., mountains, rivers, lakes, among others) were represented by spotlights, as *P. polycephalum* avoids bright light. Initially the mold filled the branching space densely, and then diluted, leaving only a network whose branches joined themselves to connect the food sources. The resulting network was strikingly similar to the Tokyo rail system. The authors conclude that *P. polycephalum* fungi are able to build optimized nets in a natural way.

D. Spatio-temporal Evolution Model for Fungi

In [15] a theoretical mathematical model is presented to help understanding the space-time dynamics of fungal network growth. Eqs. (1) to (5) show the mathematical model of Falconer et al. relating the processes of absorption, production and recycling of biomass and transport of mobile biomass:

$$D_n = \begin{cases} 10^{-7}.D_b, & n \geq n_0 \\ D_b, & n < n_0 \end{cases} \quad (1)$$

$$\frac{\partial b_i}{\partial t} = \xi \left[\frac{\partial}{\partial x} D_b \frac{\partial b_n}{\partial x} + \gamma(\alpha_n \pi^\theta - \rho_n \pi) b_n \right] + \gamma(\alpha_n \pi^\theta - \rho_n \pi) b_i \quad (2)$$

$$\frac{\partial b_n}{\partial t} = (1-\xi) \left[\frac{\partial}{\partial x} D_b \frac{\partial b_n}{\partial x} + \gamma(\alpha_n \pi^\theta - \rho_n \pi) b_n \right] \quad (3)$$

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x} D_b(n) \frac{\partial b_n}{\partial x} - (\alpha_n \pi^\theta - \rho_n \pi) b_n - (\alpha_i \pi^\theta - \rho_i \pi) b_i + (\lambda_1 b_n + \lambda_2 b_i) s \quad (4)$$

$$\frac{\partial s}{\partial t} = \omega(s_m - s) - (\lambda_1 b_n + \lambda_2 b_i) s \quad (5)$$

where, the formulations are based on the following considerations:

a. Mobile biomass diffuses in the colony and depends on a diffusion coefficient D_n, which, in turn, depends on the local concentration of mobile biomass n. D_b is a constant representing the diffusion coefficient of non-insulated immobile biomass. The value of n_0 is a constant representing the moving mass concentration threshold (Eq. (1));

b. Immobile biomass is mobilized locally at a mobilization rate ρ proportional to the local mobile biomass concentration, $\rho.\pi$, where $\pi = n/(b_n+b_i)$. The mobilization rate may vary the coefficient for ρ_n or ρ_i for regions comprising non-insulated biomass (b_n) and insulated biomass (b_i), respectively;

c. Mobile biomass is locally immobilized at an immobilization rate α as per $\alpha.\pi^\theta$. The coefficient may vary to α_n or α_i, in regions comprising non-insulated and insulated biomass respectively, and θ is a constant that regulates the immobilization sensitivity according to the moving mass concentration. Mobile biomass is converted to immobile biomass with efficiency denoted by γ;

d. Mobile biomass is produced at a rate proportional to local absorption. The rate of absorption of resources is assumed to be proportional to the local concentration of immobile biomass and the external substrate concentration (Eq. (5)).

Eq. (2) represents the dynamics of insulated immobile biomass production. The immobile biomass production rate is proportional to the diffusion coefficient, the surface biomass rate, the difference between mobile and immobile biomass conversion rates (i.e., $\alpha.\pi^\theta - \rho.\pi$), considering only insulated and non-insulated biomass regions. In the expression, the constant ξ indicates the conversion rate of non-insulated biomass to insulated biomass. Eq. (3) shows the production rate of non-insulated immovable biomass, in this case, comprising only non-insulated biomass regions, as insulated biomass does not convert to non-insulated biomass. Eq. (4) shows the dynamics of mobile biomass concentration and the conversion ratios of immobile to mobile biomass and vice versa, where λ_1 and λ_2 are the absorption rates for non-insulated and insulated biomass, respectively. Finally, equation (5) shows the dynamics of the nutrient concentration of the external substrate, where ω is the substrate replacement rate, s indicates the value of the external substrate concentration and s_m is the maximum value of this concentration.

The simulation results show that this model explores the range of types of mycelium growth by relating the processes of absorption, conversion of mobile biomass to immobile biomass and recycling of immobile biomass for different configurations in biomass production and recycling rates.

III. Fungi Bioinspired Algorithms

The ability to explore environments in search of nutrients and the ability to form and maintain adaptive networks are drawing researchers' attention to new paradigms in building functional problem-solving algorithms. In this section, we consider how the skills of fungal colonies can inspire the creation of algorithms for space searching and for communication networks.

A. Space Searching Algorithms

The combination of hyphal growth and tip branching allows some specific species of fungi to explore complex physical environments using a variety of efficient space searching algorithms. Hanson et al. [19] present a natural space search algorithm with good results obtained by studying the behavior of different species of *basidiomycete* fungi in micro-confined structures (labyrinths), of the order of 100 μm in diameter, currently found in microfluidic technology. This natural algorithm has a main structure and comprises two sub-algorithms called directional memory (DM) and collision response (CR) that simulate directional memory and branching in response to collisions, respectively, which are two features inspired by the observation of fungi while expanding and solving the maze. Similar experiments were presented with different fungi to observe variations in DM/CR sub-algorithms. It was observed that mazes can be solved by some fungal species, and what changes is the response to collision and the degree of memory.

The performance of natural spatial search algorithm has been tested and compared with some classic graph search algorithms such as the uninformed type algorithm, Depth First Search, and the informed types, A*, Best First Search, Jump Point Search and Dijkstra. To measure the algorithms efficiency, the following metrics were considered: completeness, optimality and state space. In general, the fungal algorithm showed better results only in relation to DFS, e.g., 20-40% better, depending on the maze size, but lower than the uninformed algorithms. Nevertheless, these findings suggest that research into natural space searching algorithms used by microorganisms is justified and promising [20-21].

B. The FunNet Protocol

FunNet is a protocol proposal, bio-inspired by fungal networks, that seeks to solve routing and management problems in wired communication networks, which suffer from network size growth, traffic increase and topology variation [22].

The description of hyphae behavior in FunNet is based on the original mathematical model developed by Falconer et al. [15] (see section II.D). This formulation suggests a mapping between fungal and communication networks showing how a fungal network can represent a communication network. The basic idea corresponds to establish a relationship between the structure of the mycelium and a communication network. In this way, filaments (or hyphae) can be compared to the links, the tips and the derivations of the hyphae to the routing nodes.

Routing in FunNet: The FunNet introduces an algorithm with a new routing concept. FunNet's key point is based on the idea that data flow can be described by the fungal mobile biomass transport mechanism. In this model there are no routing tables, nodes need not have information from the network as a whole, but only know who their immediate neighbors are. Thus, FunNet proposes new tools and techniques based on how the fungus grows extending its hyphae, generating derivations and self-organizing itself as a complex network structure.

Based on the mapping between fungal and communication networks, the work in [22] shows the meaning of the fungi analogies and terms applied to FunNet, as described below:

a. The fungal mycelium represents the topology of a communication network;

b. Each node has the associated parameters of mobile (M) and immobile biomass (I). Mobile biomass should be diffused in the path of a successful routing, and immobile biomass represents a node attractiveness factor for new traffic;

c. When a request to send a data packet is initiated in a communication network, an amount of mobile biomass will be generated. This amount of mobile biomass will diffuse evenly along the route over which node the data packet passed;

d. Biomass recycling in a fungal network means the transformation of mobile biomass into immobile biomass. This concept is used in communication network in the way to increase local immobile biomass concentrations;

e. The direction of a data packet sent in a communication network is associated with the transport mechanisms of mobile biomass in a fungal network. Data traffic will always flow from a region of higher mobile biomass density to one of lower density;

g. In a fungal network, biomass consumption will reduce the concentration of immobile biomass over time.

Route selection: The FunNet's route selection process uses a heuristic to calculate the next hop of the data packet; the result will be the direction of the highest concentration of immobile biomass that implies the locations with the highest transport capacity. Thus, the node with the highest local concentration of immobile biomass has greater attractiveness of data flows.

Let C_n, T_n, M_n, and I_n, respectively, be the capacity, current traffic, mobile biomass and immobile biomass, directly associated with node n. Let N_i be the set of nodes adjacent (neighbors) to node i. Eq. (6) shows the calculation of probability $P_{i,n}^{d}$ which indicates the probability of node i select a certain neighbor n as the next hop, toward a destination d.

$$P_{i,n}^{d} = \frac{G_n}{\sum_{j \in N_i} G_j}, \quad \forall n \in N_i \tag{6}$$

where,

$$G_j = C_j + I_j - T_j \tag{7}$$

Mobile **biomass diffusion:** A constant amount E of mobile biomass will be generated when a data packet needs to be sent to its destination. When the data packet reaches its destination, mobile biomass spreads evenly across the nodes through which the packet passed, i.e., these nodes will increase their value of M by E/R, where R is the number of nodes in the route.

Biomass recycling: Biomass recycling represents the changing of level of immobile biomass, which is influenced by current network status. In FunNet, biomass recycling happens after every successful routing and will transfer (for each node k of the route) an amount of mobile biomass into immobile biomass, i.e., each node will have its mass M_k reduced by λ and its mass I_k increased by the same amount, where

$$\lambda = \left[\alpha.\left(\frac{M_k + T_k}{I_k}\right)^{\theta} - \rho.\left(\frac{M_k + T_k}{I_k}\right)\right].I_k \tag{8}$$

Biomass consumption: Biomass consumption reduces the value of immobile biomass when its value is larger than a threshold, i.e.,

$$I_k = I_k - K, \quad \text{if} \quad I_k > \varepsilon \tag{9}$$

The quantities α, ρ, θ, K and ε are FunNet's operating parameters. Therefore, the processes of diffusion, recycling and consumption of biomass, characteristic of fungi, constitute a learning process capable of refining routing decisions.

IV. A Functional Routing Algorithm

When considering the FunNet proposal [22], it is observed that the research is still in its early stages and the article does not provide an in-depth description of the model's operation. At first, the Eq. (7) directly relates different quantities. Capacity and traffic quantities interact directly with a biomass quantity (immobile biomass) without data normalization. The same is true in Eq. (8) where it relates traffic to mobile and immobile biomass. In addition, the parameter θ makes the convergence of the set of equations a nonlinear process, which can cause great instability in route maintenance. These aspects are of fundamental importance for the correct operation of the system. Route discovery and maintenance are not separate procedures, but are carried out concomitantly by using Eqs. (6) to (9). In addition, the article [22] does not perform an in-depth analysis of FunNet performance, but simply presents the average number of hops for each successful routing.

A. The HyphaNet Protocol

This section investigates a functional routing algorithm for wireless networks, called HyphaNet. HyphaNet is a multipath protocol whose algorithm converges to the most advantageous route while exploring the search space. It has specific procedures for route discovery (based on the diffusion of RREQ and RREPLAY packets) and for route maintenance and optimization (based on diffusion, recycling and biomass consumption processes) [10].

By considering wireless networks, in HyphaNet the concepts of capacity and traffic are replaced by the concepts of storage and load. Let B_j be the size and L_j the average number of packets present in the network interface buffer (MAC) associated with node j. Let $ABS_j = 1 - L_j/B_j$ be the available buffer space. We then adopt $G_j = (I_j)^{\mu}.(ABS_j)^{\Omega}$, which favors the best routes without incurring in normalization problems.

In HyphaNet, after every successful data routing to the destination, the following equations are updated (for each node k of the route):

$$\lambda = \alpha . M_k \tag{10}$$

$$M_k = M_k + E.\Lambda \tag{11}$$

$$M_k = M_k - \lambda \tag{12}$$

$$I_k = I_k + \lambda \tag{13}$$

$$I_k = \beta . I_k \tag{14}$$

The objective function $\Lambda = \sum_j ABS_j / R^2$ provides the quality of the route, where j corresponds to the nodes in this route, Eq. (10) allows eliminating nonlinearities in the convergence of the algorithm, Eqs. (11) to (13) represent the biomass diffusion and recycling processes and Eq. (14) describes the consumption of immobile mass. The quantities α, β, μ and Ω are HyphaNet's operating parameters.

B. Convergence Analysis

The action of the HyphaNet over time allows establishing that mobile and immobile mass updates occur, respectively, according to the following equations:

$$M^{(n)} = (1-\alpha).M^{(n-1)} + E.\Lambda^{(n)}, \quad n \geq 1 \tag{15}$$

$$I^{(n)} = \beta.\left(I^{(n-1)} + \alpha.M^{(n-1)}\right), \quad n \geq 1 \tag{16}$$

It is noted that Eq. (15) corresponds to a form of exponential moving average (EMA) of the function Λ. In turn, Eq. (16) is a form of EMA for mobile biomass (resulting in a double EMA of function Λ).

Applying the recursive principle in Eq. (15) yields:

$$M^{(n)} = (1-\alpha)^n.M^{(0)} + E.\sum_{i=0}^{n-1} (1-\alpha)^i \Lambda^{(n-i)}, \quad n \geq 1 \tag{17}$$

Performing the same procedure for Eq. 16 gives:

$$I^{(n)} = \beta^n.(I^{(0)} + \alpha M^{(0)}).+\alpha.\sum_{j=1}^{n-1} \beta^j M^{(n-j)}, \quad n \geq 1 \tag{18}$$

where: $M^{(0)}$ and $I^{(0)}$ are the initial values of mobile and immobile biomass, respectively. Substituting Eq. (17) into Eq. (18) gives:

$$I^{(n)} = \beta^n.(I^{(0)} + \alpha M^{(0)}).+\alpha(1-\alpha)^n.\sum_{j=1}^{n-1}\left(\frac{\beta}{1-\alpha}\right)^j M^{(0)} \\ +\alpha E.\sum_{j=1}^{n-1}\sum_{i=0}^{n-j-1} (1-\alpha)^i \beta^j \Lambda^{(n-j-1)}, \quad n \geq 1 \tag{19}$$

In order to evaluate the convergence of the system, we can determine the step response by doing $\Lambda^{(n)} = \overline{\Lambda}.H(n)$, where $\overline{\Lambda}$ is the average of the objective function over a time interval, and $H(n)$ is the Heaviside function. If $\alpha < 1$ e $\beta < 1$, disregarding the values of $M^{(0)}$ and $I^{(0)}$, the immobile biomass converges to:

$$\lim_{n\to\infty} I^{(n)} = \frac{\beta.E.\overline{\Lambda}}{1-\beta} \tag{20}$$

Considering a set of routes between origin s and destination d, where the route whose next hop p is the most favorable, i.e., $\overline{\Lambda}_p > \overline{\Lambda}_q, \forall p \neq q,$ it is concluded that the protocol acts correctly, because $I_p^{(n)} > I_q^{(n)}, n \to \infty,$ resulting in $P_{s,p}^d > P_{s,q}^d$.

The values of α and β are fundamental in the protocol performance. If α is small and β is high, the immobile biomass will converge slowly and the routes may become more unstable. On the other hand, if α is high and β is small, the routes may not react to topological variations. Fig. 3 shows the behavior of the immobile biomass (normalized) for a set of values of α and β (where $I_{norm} = (1\text{-}\beta).I/\beta$ and $E.\overline{\Lambda} = 1$), considering $M^{(0)} = 0$ and $I^{(0)} = 0$.

C. Proof of Concept

In HyphaNet the most advantageous routes tend to add more immobile biomass. In order to prove the algorithm convergence, this section shows simulation results considering a 10-node fixed topology, as shown in Fig. 4. For the purposes of this validation, and without loss of generality, it was considered that $\mu = 2.0$, $\Omega = 1.0$, $\alpha = 0.1$ and $\beta = 0.95$.

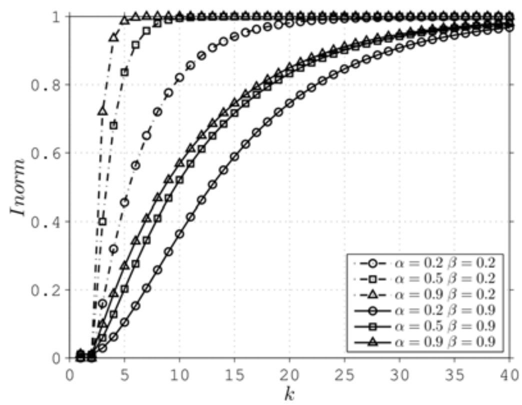

Figure 3. Immobile mass (normalized) versus number of HyphaNet equation system updates

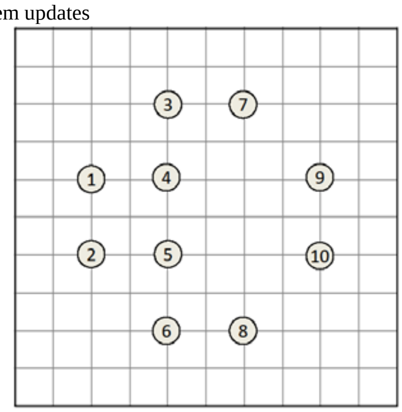

Figure 4. The 10-node test topology

HyphaNet was simulated using the NS-2.35 [23] network simulator considering IEEE 802.11 standard [24-25]. The radio transmission range has been set to a maximum of 150 m. The topology has source on node 1 and destination on node 10. This topology allows observing, step by step, the behavior of the algorithm in creation and route selection processes and its effectiveness in convergence. The shortest route is the path 1-5-8-10. In this scenario, the common sense shows that this route and its node components should register higher selection probabilities and, consequently, higher utilization rates. We repeated each simulation 60 times and took their average as simulation results. Finally, we computed 95% confidence interval for each performance data and a confidence interval bar is plotted for each data point of the average curves.

Fig. 5 and Fig. 6 show graphs of probability estimates and node utilization. For each simulation all moments of the selection process in which the probability of each node appears were recorded, obtained as a function of its attractiveness. Utilization was obtained as a function of the number of times the node was selected as the next hop in relation to the total data packets transmitted.

According to the topology, at the beginning of a data transmission, the source node can select a node from nodes 2, 3, 4, and 5, which are within the radio range. In this case, node 5 achieved approximately 60% utilization with an average probability around 50% during the simulations. The average probability of node 8 is almost 100% because this is the only route seen by node 5. Similarly, nodes 7 and 9 have high average probabilities because they are unique routes when one of nodes 3 and 4 is selected. Therefore, the probability estimates and utilization values at node 5 show that there is convergence to the best route.

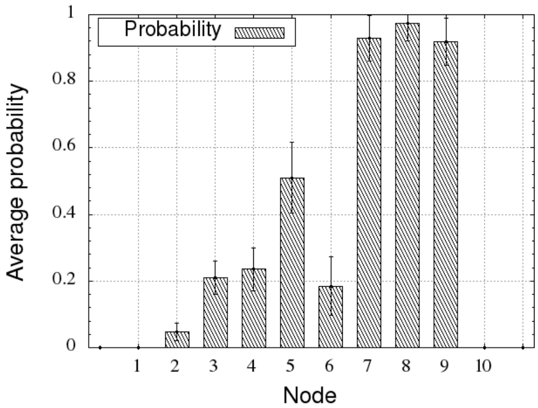

Figure 5. Probability of selection

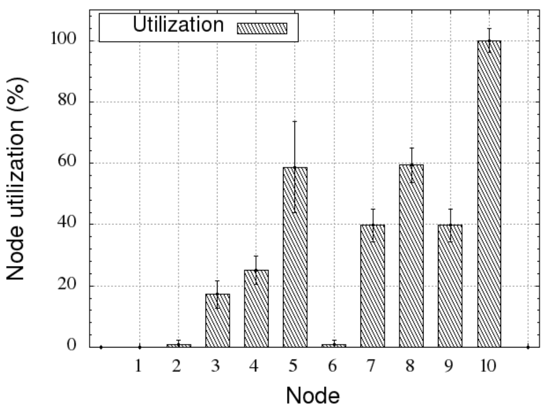

Figure 6. Use of the node in the route to the destination

Fig. 7 shows the use of the routes between source and destination nodes. This information was obtained by recording the routes used during each packet sent. The routes are the following: R1: 1-2-6-8-10, R2: 1-5-6-8-10, R3: 1-5-8-10, R4: 1-3-7-9-10, and R5: 1-4-7-9-10. Thus, it was possible to calculate the percentage of utilization of each route in relation to the total data packets transmitted. For example, it is observed that route 3, relative to the shortest path, obtained around 55% of occupation in simulations, showing that the algorithm converged to the best route.

D. HyphaNet Evaluation

In this section, we present a set of simulations results demonstrating the effectiveness of our proposal. The simulations ran by 180 seconds considering the same traffic pattern, but with different mobility scenarios. Average values were obtained from simulations with 120 rounds and with 95% confidence interval. The configured simulation parameters are shown on Table I.

The traffic pattern used was based on CBR/UDP connections between randomly chosen source-destination pairs. Once started the sources, the transmission lasts until the end of the simulation. The scenario was tested using this traffic pattern, with variations in the sources send rate.

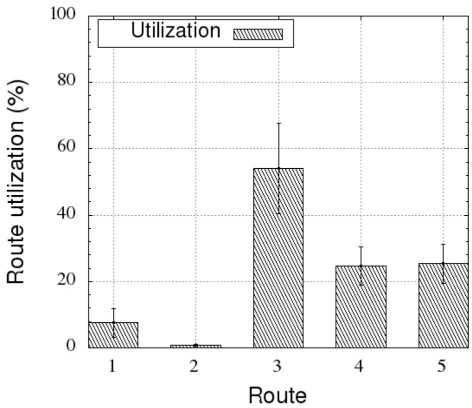

Figure 7. Use of routes

TABLE I. SETTING OF THE SIMULATION PARAMETERS

Parameters	Settings
Simulator	NS-2.35
Number of simulation rounds	120 rounds of 180 s
Simulation area	1000 m × 1000 m
Number of nodes	100 nodes
Number of sources	10 nodes
Mobility model	random way point
Nodes speed range	1-20 m/s
Transmission range	250 m
Packet length	512 bytes
Traffic pattern	CBR/UDP
Radio propagation model	two ray ground
MAC/PHY layer	IEEE 802.11b
Transmission rate	11 Mbps
Buffer size (MAC)	50 packets

Two routing protocols were selected for comparison purposes: AODV [26], being a well-known classic protocol with widespread utilization; and SARA [27], as an example of a high-performance ACO-based protocol. Both have an implementation in the NS-2 simulator. SARA protocol configuration details come from [27]. HyphaNet configuration details are those of Section IV.C.

The routing protocols were evaluated based on the following metrics:

- *Packet Delivery Rate*: It is the ratio of data packets that are successfully delivered to a destination to the number of data packets that have been sent out by the sender. It is desired that maximum number of data packets has to be reached to the destination.

- *Protocol's Routing Overhead*: It is the number of routing packets transmitted to the total number of packets (data + control) sent to the destination. A good routing protocol should incur lesser routing overhead.
- *Average end-to-end delay*: It refers to the average time taken for a packet to be transmitted across a network from source to destination. A good routing protocol should incur lesser average end-to-end delay.

Fig. 8, Fig. 9 and Fig. 10 present the results obtained for the performance metrics versus send rates (in packets/s). HyphaNet presented results very close to SARA considering packet delivery rate and end-to-end delay; both of them were better than AODV in this case. Considering the overhead, HyphaNet presented results very close to AODV and both were better than SARA.

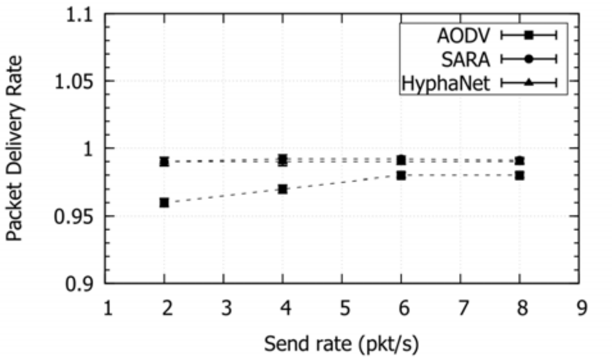

Figure 8. Packet delivery rate versus send rates

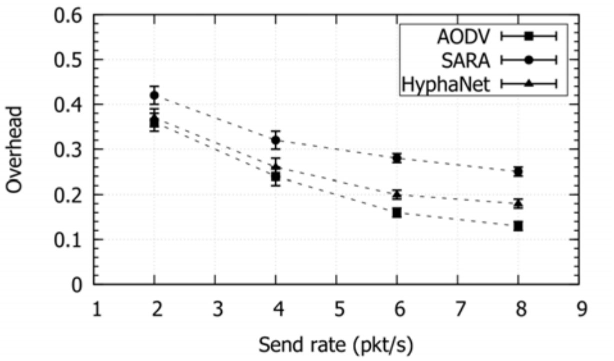

Figure 9. Routing overhead versus send rates

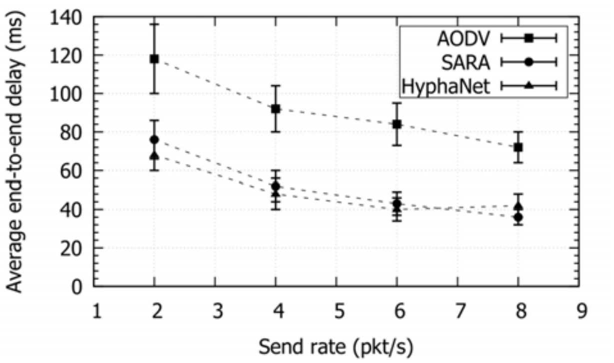

Figure 10. End-to-end delay versus send rates

V. Conclusion

Inspiration in natural systems has attracted the interest of researchers for the development of new algorithms seeking efficient solutions to the most diverse problems. Recently a new frontier of nature has been a source of inspiration for the development of solutions: fungi. Taking inspiration from fungi, this paper considered the process of filamentous fungus growth as metaphor for building a functional routing algorithm for wireless communication networks, the HyphaNet. It has specific procedures for route discovery and for route maintenance and optimization. Analytical modeling and validation tests proved that HyphaNet converges to more advantageous routes while exploring the search space. In simulations, HyphaNet has shown that it can deliver good performance on the metrics: packet delivery rate, average end-to-end delay and overhead.

Future work will explore a more extensive group of simulations focusing on deeply verifying the effect of the control parameters on the performance of the proposed protocol and the study of approaches that may reduce the routing overhead.

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