Slime Mould Approximates Malaysian Expressways: Is There a Bio-logic Behind the Transport Network?

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***Abstract*—Malaysian expressways network is designed based on human logic, but does the Malaysian transport system have anything in common with biological transport systems? We employ slime mould Physarum polycephalum in our search for an answer. We represent twenty major urban areas in Malaysia with sources of nutrients and inoculate slime mould in Kuala Lumpur. We wait till the slime mould colonises all urban areas and then analyse the network of slime mould's protoplasmic tubes and compare it with existing transport network of Malaysia. Experiments with Physarum polycephalum shows that the protoplasmic network is largely a super-graph of most famous planar proximity graphs and include a minimum spanning tree. With regards to man-made transport network, the slime mould approximates almost all major transports routes. Our results do not have any immediate engineering applications but shed light onto 'living logic' of transport systems and could contribute to future planning of transport networks.**

Keywords-biological transport networks; slime mould; unconventional computing

I. INTRODUCTION

Plasmodium is a vegetative stage of acellular slime mould *Physarum polycephalum*. This is a single cell with many nuclei. The plasmodium fees on microscopic particles [1]. During its foraging behavior the plasmodium spans scattered sources of nutrients with a network of protoplasmic tubes. The protoplasmic network is optimized to cover all sources of food and to provide a robust and speedy transportation of nutrients and metabolites in the plasmodium body. The plasmodium's foraging behavior can be interpreted as computation. Data are represented by spatial configurations of attractants and repellents, and results of computation by structures of protoplasmic network formed by the plasmodium on the data sites [2-4]. The problems solved by plasmodium of *Physarum polycephalum* include shortest path [2,3], implementation of storage modification machines [4], Voronoi diagram [5], Delaunay triangulation [4], logical computing [6,7], and process algebra [8].

Previously [9], we have evaluated a road-modeling potential of *Physarum polycephalum*, however, no conclusive results were presented back in 2007. A step forward biological-approximation, or evaluation, of man-made road networks was done in our previous papers on approximation of motorways/highways in United Kingdom [10], Mexico [11], United States [12], Germany [13], Australia [14], Netherlands [15], Africa [16], and China [17] by plasmodium of *Physarum polycephalum*. For these countries we found that, in principle, network of protoplasmic tubes developed by plasmodium matches, at least partly, network of man-made transport networks. However, a country's shape and spatial configuration of urban areas, which are experimentally represented by sources of nutrients, might play a key role in determining exact structure of plasmodium networks. Also, we suspect that a degree of matching between Physarum networks and motorway networks is determined by original government designs of motorways in any particular country. This is why it is so important to collect data on development of plasmodium networks in all major countries, and then undertake a comparative analysis. Hence, in this paper, we have chosen Malaysian expressways network as a field test. Note that the slime mould approach is not probabilistic and produces the same networks when parameterized in the same way.

DOI 10.5013/IJSSST.a.15.04.03

ISSN: 1473-804x online, 1473-8031 print

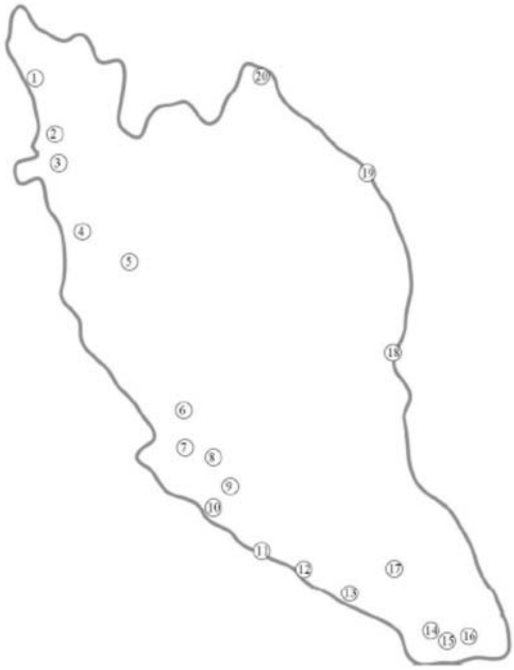
The paper is structured as follows. We explain experimental setup in Section 2. Section 3 provides analysis of protoplasmic networks developed by *P. polycephalum* on Malaysian cities. In Section 4, we compare protoplasmic networks with man-made expressways networks. The slime mould and manmade transport networks are analysed in terms of planar proximity graphs in Section 5. In Section 6, we present result of laboratory experiments on transport network's response to propagating contamination with epicentre in Kuantan.

II. EXPERIMENTAL

Plasmodium of *Physarum polycephalum* is cultivated in plastic container, on paper kitchen towels moistened with still water, and fed with oat flakes. For experiments, we use 120 × 120 mm polystyrene square Petri dishes and 2% agar gel (Select agar, by Sigma Aldrich) as a substrate. Agar plates, about 2-3 mm in depth, are cut in a shape of Malaysia. We selected 20 most populated major urban areas where the configuration of these areas is shown in Fig. 1a. The urban areas are as follows:

1. Alor Star
2. Sungai Petani
3. Kulim area, including Kulim, Bukit Mertajam and Butterworth
4. Taiping
5. Ipoh
6. Rawang
7. Kuala Lumpur area
8. Kajang area, including Kajang and Semenyih
9. Seremban
10. Port Dickson
11. Bandar Melaka
12. Muar area, including Muar and Ayer Itam
13. Batu Pahat
14. Skudai area, including Skudai and Senai
15. Johor Bahru area, including Johor Bahru and Ulu Tiram
16. Pasir Gudang
17. Kluang
18. Kuantan
19. Kuala Terengganu
20. Kota Bahru

To represent areas of **U**, we place oat flakes in the positions of agar plate corresponding to the areas. At the beginning of each experiment an oat flake colonized by plasmodium is placed in Kuala Lumpur area. We undertook 30 experiments. The Petri dishes with plasmodium are kept in darkness, at temperature 22-25ºC, except for observation and image recording. Periodically, the dishes are scanned with an Epson Perfection 4490 scanner and configurations of protoplasmic networks are shown in Fig. 1b.



(a)

(b)

Fig. 1. (a) Outline map of Malaysia with major urban areas **U** shown by encircled numbers. (b) Urban areas, represented by oat flakes, are colonized by slime mould of *Physarum polycephalum*.

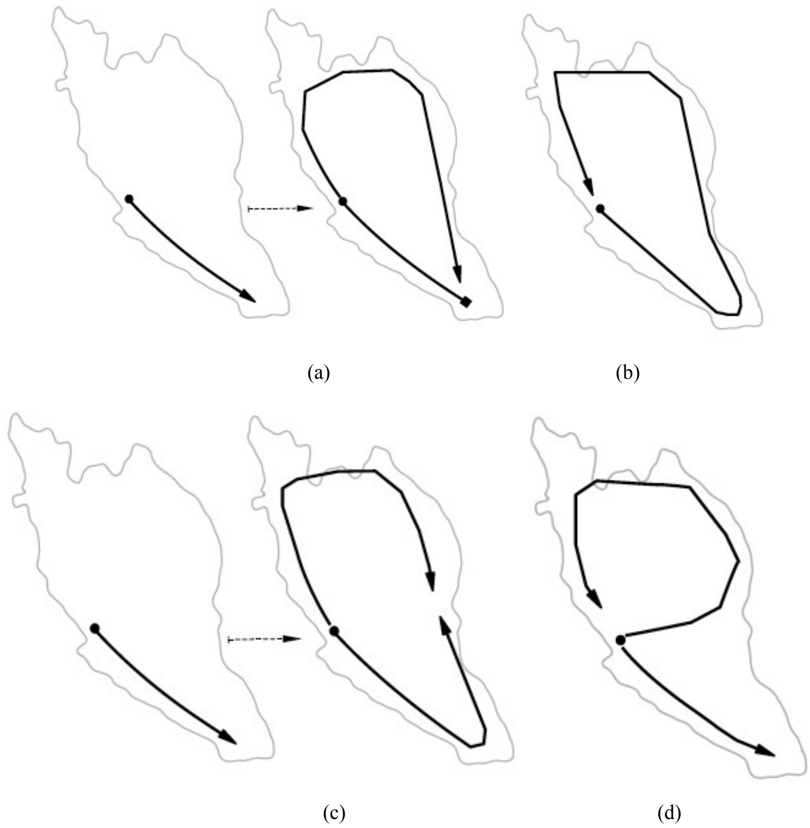


Fig. 2. Scenario of colonisation of U by plasmodium of *P. polycephalum*.

III. Physarum Transport Networks on Malaysian Cities

In DGSA, a new approach is introduced to update agent's position. The direction and velocity of an agent will determine the candidates of the next position. Specifically, an agent moves in the positive direction if the velocity value is positive. Otherwise, the agent moves in the negative direction. The velocity of the agent determines the candidate of the next position and then, position update is done randomly based on the candidate of the next position.

We recorded four scenarios of slime mould colonizing urban areas **U**.

- SENES: south-east then north-east and then south (Fig. 2a), observed in thirteen experiments.
- SENW: south-east then north and north-west (Fig. 2b), observed in eleven experiments.
- SE-T-NW: south-east and at the same time north-west (Fig. 2c), observed in five experiments.
- SEWN: sout-east and at the same time west and then north/north-west (Fig. 2d), observed in one experiment.

SENES scenario is executed by slime mould in over 43% of experiments. The slime mould propagates from Kuala Lumpur to Rawang and Kajang areas (Fig. 3a and 3e). It does not propagate further north from Rawang but heads south and colonises Seremban, Port Dickson, Bandar Melaka, Muar, Batu Pahat, Skudai and Kluang, Johor and Pasir Gudang. The plasmodium becomes 'blocked' in Pasir Gudang and does not make any feasible attempts to move towards closed unoccupied area of Kuantan (Fig. 3b and Fig. 3b). When 'blocked' in Pasir Gudang the plasmodium re-activates its active zone in Rawang, builds a transport link connecting Rawang with Ipoh. It then propagates further south and colonises Taiping and Kuliam areas (Fig. 3c and 3g). At this point of spanning **U** the slime mould branches: usually norther branch travels towards Sungai Petani and Alor Star areas and eastern branch propagates towards Kota Bharu. Transport links between Kota Bharu with Kuala Terengganu and Kuantan complete colonisation of **U** (Fig. 3d and 3h).

DOI 10.5013/IJSSST.a.15.04.03

ISSN: 1473-804x online, 1473-8031 print

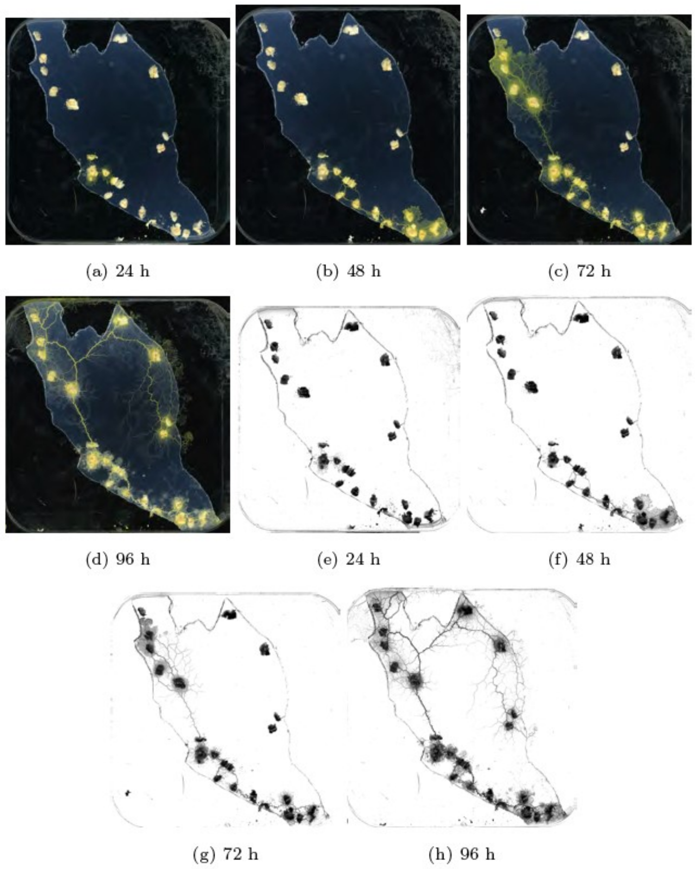


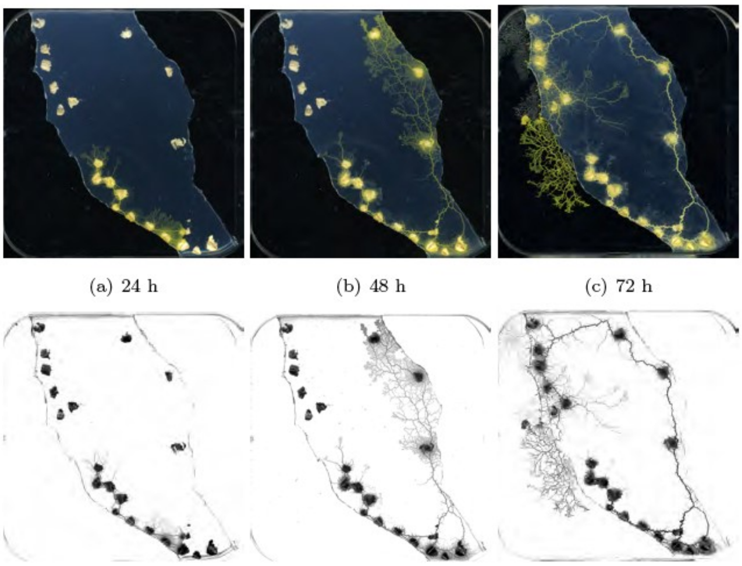
Fig. 3. Snapshots of slime mould colonising urban areas **U** by SENES scenario. The images are recorded in 24 h intervals after inoculation of plasmodium in Kuala Lumpur. (a-d) original not-enhanced scanned images. (e-h) enhanced images converted to grey-scale levels.

SENW scenario occurs in 36% of experiments. Initial stage of the colonisation (Fig. 4a and Fig. 4d) is similar to SENES scenario: urban areas from Kuala Lumpur to Pasir Gudang are colonised. From Kluang and/or Pasir Gudang plasmodium propagates toward Kuantan and then colonises Kuala Terenganu and Kota Bahru (Fig. 4b and Fig. 4e). Then plasmodium propagates toward Alor Star and Kulim areas and colonises the remaining urban areas (Fig. 4c and Fig. 4d).

Both clockwise and anti-clockwise colonisation of **U** is performed by plasmodium in scenario SE-TNW, in 17% of experiments. Starting in Kuala Lumpur, as shown in Fig. 5, slime mould colonised **U** simultaneously along the following routes:

- Kuala Lumpur — Kajang — Seremban — Port Dickson — Bandar Melaka — Muar — Batu Prahat – Skudai and Kluang — Johor Bahru — Pasir Gudang — Kuantan — Kuala Terengganu.
- Kuala Lumpur — Ipoh — Taiping — Kulim, Sungai Petani and Alor Star — Kota Bahru.

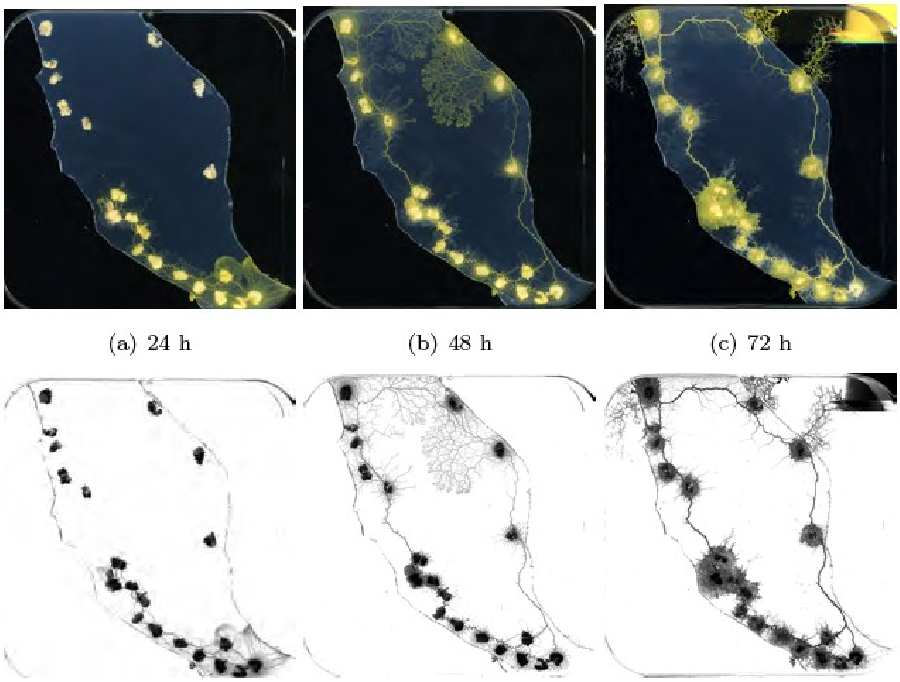
To generalise our experimental results we constructed a Physarum graph with weighted-edges. A Physarum graph is a tuple **P** = <**U**, **E**, ω>, where **U** is a set of urban areas, **E** is a set edges, and : **E** → [0, 1] associates each edge of **E** with a probability (or weights). For every two regions a and b from **U** there is an edge connecting a and b if a plasmodium's protoplasmic link is recorded at least in one of k experiments, and the edge (a,b) has a probability calculated as a ratio of experiments where protoplasmic link (a,b) occurred in the total number of experiments k = 30. For example, if we observed a protoplasmic tube connecting areas a and b in 12 experiments, the weight of edge (a,b) will be $\omega(a,b) = 12/30$. We do not take into account the exact configuration of the protoplasmic tubes but merely their existence. Further we will be dealing with threshold Physarum graphs **P**(θ) = <**U**, T(**E**), $\boldsymbol{\omega}$, θ>. The threshold Physarum graph is obtained from Physarum graph by the transformation: T(**E**) $= \{e \in \mathbf{E} : \boldsymbol{\omega}(e) > \theta\}$. That is all edges with weights less than or equal to θ are removed. Examples of threshold Physarum graphs for various values of θ are shown in Appendix.



(a) 24 h (b) 48 h (c) 72 h

(d) 24 h (e) 48 h (f) 72 h

Fig. 4. Snapshots of slime mould colonising urban areas **U** by SENW scenario. The images are recorded in 24 h intervals after inoculation of plasmodium in Kuala Lumpur. (a, b, c) original not-enhanced scanned images. (d, e, f) enhanced images converted to grey-scale levels.



(a) 24 h (b) 48 h (c) 72 h

(d) 24 h (e) 48 h (f) 72 h

Fig. 5. Snapshots of slime mould colonising urban areas **U** by SE-T-NW scenario. The images are recorded in 24 h intervals after inoculation of plasmodium in Kuala Lumpur. (a, b, c) original not-enhanced scanned images. (d, e, f) enhanced images converted to grey-scale levels.

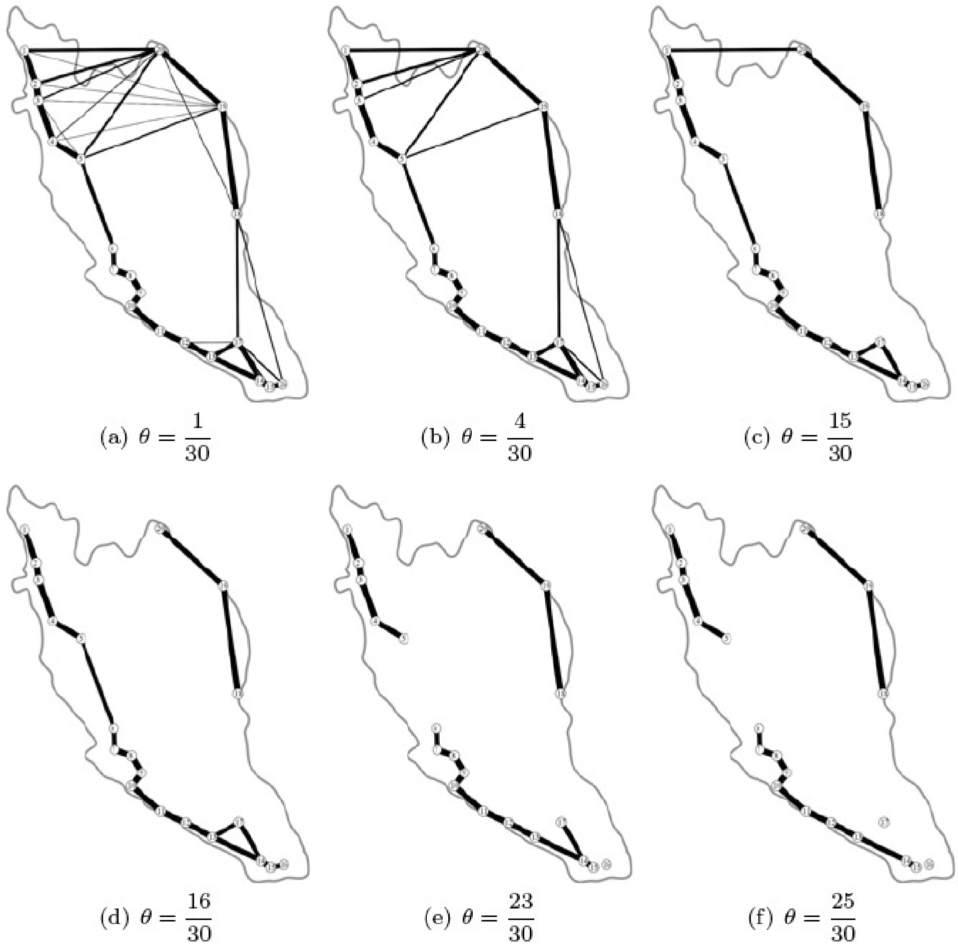


Fig. 6. Physarum graphs $\mathbf{P}(\theta)$ for selected values of θ. Weights of edges are reflected in the width of their line representations.

A raw Physarum graph $\mathbf{P}(1/30)$ consists of a planar southern part and non-planar north part as shown in Fig. 6a. The non-planar component is located north of Ipoh on the east and north of Kuantan on the west. The graph becomes planar when θ increases to 4/30 as shown in Fig. 6b. When we remove edges appeared in less than half of experiments, i.e. those with weighs less than 15/30, the Physarum graph becomes almost linear and the only cycle in the south is formed by Batu Pahat, Skudai and Kluang urban areas, as shown in Fig. 6b.

Finding 1. *Transport network built by plasmodium of P. polycephalum on twenty major urban areas of Malaysia consists of a linear chain spanning urban areas along the coast and a single cycle.*

Physarum graph becomes disconnected when θ = 16/30 as shown in Fig. 6d. One component is a three node chain, spanning Kuantan to Kuala Terengganu to Kota Bahru. Second component is a chain from Alor Setar to Batu Pahat, cycle Batu Pahat, Skudai and Kluang and a segment Johor Bahru to Pasir Gudang. The reason for the formation of two disconnected components is not because slime mould builds disconnected protoplasmic networks but because in almost every experiment plasmodium chooses different ways to connect east and west urban areas in the north of Malaysia, thus no single edge there is represented in over half of experiments.

The graph becomes planar, yet disconnected but without isolated nodes, for θ = 23/30 as shown in Fig. 6e. Urban area Kluang becomes isolated vertex for θ = 23/30 as shown in Fig. 7f. We call an edge stable when it is represented by slime mould's protoplasmic tubes in over 80% of laboratory experiments.

Finding 2. *A stable transport network of Malaysia, represented by plasmodium of P. polycephalum, consists of three disconnected chains:*

Rawang, Kuala Lumpur, Kajang, Seremban, Port Dickson, Bandar Melaka, Muar, Batu Pahat, Skudai, Johor Bahru, and Pasir Gudang;

Alor Star, Sungai Petani, Kulim, Taiping, and Ipoh; Kota Bahru, Kuala Terengganu and Kuantan.

(a) (b) (c)

Fig. 7. (a) Graph **H** of Malaysian expressway network, **H**. (b) Intersections of the expressways graph **H** and Physarum graphs **P**(θ), **H** ∩ **P**(θ), θ = 1/30, … , 15/30. (c) Intersections of the expressways graph **H** and Physarum graphs **P**(θ), **H** ∩ **P**(θ), θ = 23/30, … , 25/30.

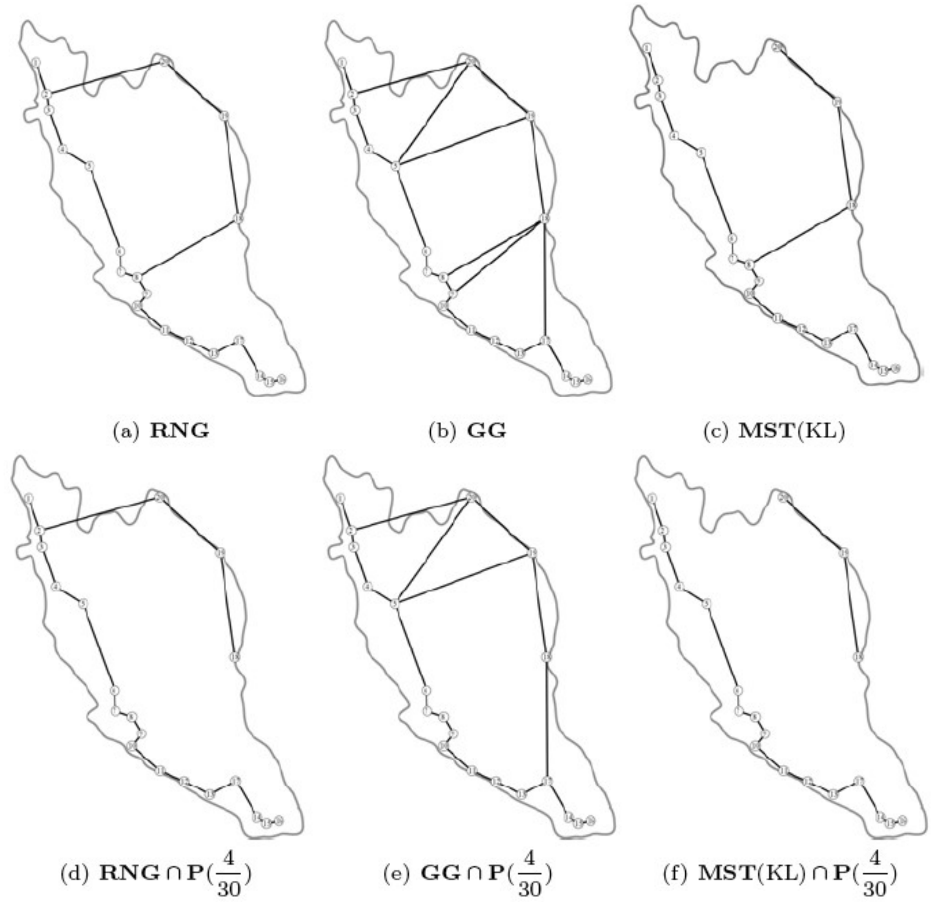


Fig. 8. Proximity graphs constructed on sites of **U** and their intersection with planar Physarum graph **P**(4/30). (a) Relative neighbourhood graph (b) Gabriel graph (c) Minimum spanning tree rooted in Kuala Lumpur (d) Relative neighbourhood graph (e) Gabriel graph (f) minimum spanning tree rooted in Kuala Lumpur.

IV. Slime Mould Versus Malaysian Motorways

The graph **H** of Malaysian expessway network, as shown in Fig. 7, is constructed as follows. Let **U** be a set of urban regions/cities; for any two regions *a* and *b* from **U**, the nodes *a* and *b* are connected by an edge (*ab*) if there is an expressway starting in vicinity of *a*, passing in vicinity of *b*, and not passing in vicinity of any other urban area $c \in$ **U**. In the case of branching, that is, an expressway starts in *a*, goes in the direction of *b* and *c*, and at some point branches towards *b* and *c*, we then add two separate edges (*ab*) and (*ac*) to the graph **H**. The expressway graph is planar, as shown in Fig. 7. Few cities of **U** have no outgoing or incoming expressways. Therefore, in these few cases we were forced to use federal roads. The following edges of the the graph **H** correspond to federal roads:

- Batu Pahat – Kluang,
- Kuantan – Kuala Terengganu,
- Kuala Terengganu – Kota Bahru.

Finding 3. *Slime mould P. polycephalum approximates almost all edges of the expressway graph. Man-made transport links (Rawang – Port Dickson) and (Seremban – Bandar Melaka) are never represented by protoplasmic tubes.*

The above finding comes from the straightforward comparison of generalised Physarum graphs in Fig. 6 and the expressway graph **H** in Fig. 7. Essentially, P. polycephalum approximates 17 of 19 edges of the expressway graph **H**. Such a good degree of approximation may be due to very particular arrangement of major urban areas along coastal lines of Malaysia. This configuration of the sources of nutrients causes slime mould to link the sources rather by a singe chain with few if any branchings.

Finding 4. *Chains of man-made expressways (Alor Star – Port Dickson) and (Bandar Melaka – Pasir Gudang) are approximated by slime mould of P. polycephalum in over half of laboratory experiments.*

Finding 5. *Chains of man-made federal roads (Kuantan – Kota Bharu), and expressways (Alor Star – Ipoh), (Bandar Melaka – Skudai) and (Rawang – Port Dickson) are approximated by slime mould P. polycephalum in over 80% of experiments.*

V. Proximity Graphs, Slime Mould and Malaysian Motorways

A planar graph consists of nodes which are points of the Euclidean plane and edges which are straight segments connecting the points. A planar proximity graph is a planar graph where two points are connected by an edge if they are close in some sense. A pair of points is assigned a certain neighbourhood, and points of the pair are connected by an edge if their neighbourhood is empty. Here, we consider the most common proximity graph as follows.

- GG: Points *a* and *b* are connected by an edge in the Gabriel Graph **GG** if disc with diameter *dist*(*a*,*b*) centred in middle of the segment *ab* is empty [18, 19], as shown in Fig. 4a.
- RNG: Points *a* and *b* are connected by an edge in the Relative Neighbourhood Graph **RNG** if no other point *c* is closer to *a* and *b* than *dist*(*a*,*b*) [20] as shown in Fig. 4b.
- MST: The Euclidean minimum spanning tree (MST) [21] is a connected acyclic graph which has minimum possible sum of edges' lengths, as shown in Fig. 4b. In general, the graphs relate as **MST** ⊆ **RNG** ⊆ **GG** [19, 20, 22]. This is called Toussaint hierarchy.

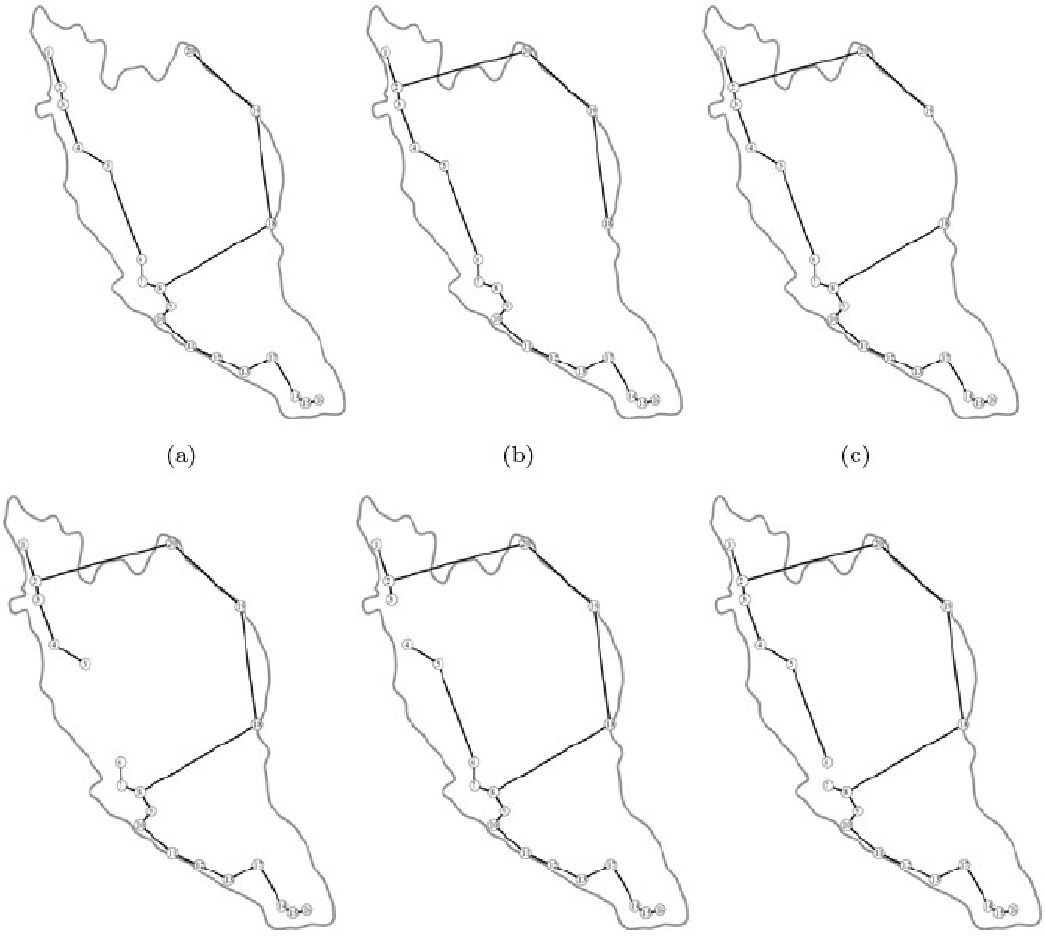
A β-skeleton **B**(β), $\beta \geq 1$, is a planar proximity undirected graph of an Euclidean point set where nodes are connected by an edge if their lune-based neighborhood contains no other points of the given set [23]. Given a set **U** of planar points, for any two points *p* and *q*, we define β-neighborhood $U_\beta(p,q)$ as an intersection of two discs with radius $\beta|p-q|/2$ centered at points $((1-\beta/2)p, (\beta/2)q)$ and $((\beta/2)p, (1\beta/2)q)$, $\beta \geq 1$ [22-23]. Points *p* and *q* are connected by an edge in β-skeleton if the pair's β neighborhood contains no other points from **V**.

Finding 6. *Minimum spanning tree rooted from Kuala Lumpur and relative neighbourhood graph would be subgraphs of Physarum graph P(4/30) if the Physarum graph had edge (Kajang, Kuantan).*

Finding 7. *Gabriel graph would be subgraph of Physarum graph P(4/30) if the Physarum graph had two edges: (Kajang, Kuantan) and (Seremban, Kuantan).*

This can be demonstrated by direct comparisons of intersections of proximity graphs and Physarum graph **P**(4/30), as shown in Fig. 8d, Fig. 8e, and Fig. 8f with original proximity graphs shown in Fig. 8a, Fig. 8b, and Fig. 8c and taking into account Toussaint hierarchy. With regards to spanning tree even stronger claim can be made: **MST**(KL) ⊂ **P**(15/30). That is a minimum spanning rooted in Kuala Lumpur is almost subgraph of robust slime mould transport network but edge (Kajang, Kuantan). Looks like transport link from Kajang to Kuantan is essential from planar proximity graphs point of view but it is not important for slime mould based transport networks.

Is tree rooted in Kuala Lumpur really minimum spanning tree? To get an answer we built spanning trees rooted in all sites of **U** as shown in Fig. 9. We found that there are six morphologies of trees with lengths (sum of edge lengths) varying from normalised 1, trees rooted in Rawang and Kuala Lumpur shown in Fig. 9a, trees rooted in Alor Star and Sungai Petani shown in Fig. 9f. Amongst all possible trees only tree rooted in Kulim or Taiping does not contain edge (Kajang, Kuantan), as shown in Fig. 9b. These tree is not strictly minimal but it is just 1% longer then minimum spanning tree rooted in Rawang and Kuala Lumpur. This means that edge (Kajang, Kuantan) does not really contribute to minimality of the spanning trees constructed on **U**.



(a) (b) (c)

(d) (e) (f)

Fig. 9. Spanning trees rooted in sites of **U** and their relative lengths l. (a) Rawang and Kuala Lumpur, $l = 1.0$ (b) Kulim and Taiping, $l = 1.01$ (c) Ipoh, $l = 1.02$ (d) Kuala Terengganu and Kota Bahru, $l = 1.04$ (e) Kajang, Seremban, Port Dickson, Bandar Melaka, Muar, Batu, Skudai, Johor Bahru, Kluang and Kuantan, $l = 1.10$ (f) Alor Star and Sungai Petani, $l = 1.13$.

Finding 8. *Minimum spanning tree rooted in Kulim or Taiping is a subgraph of robust Physarum graph P(15/30).*

Thus, we can conclude that slime mould base transport network on **U** includes minimum network.

We introduced β-skeletons in this paper in a hope to uncover an intrinsic relation between θ parameter of generalised Physarum graphs $\mathbf{P}(\theta)$ and β parameter of β-skeletons. Parameter θ governs reliability of an edges by removing edges which frequency in laboratory experiments is less than θ. Parameter β reflects a size and shape of a lune determining proximity neighbourhood of nodes [23]. In laymen terms, the larger β the more narrow and longer is lune between two neighbouring points. Increase in θ and β leads to decrease in a graph's connectivity. By comparing generalised Physarum graphs for θ up to 30 and β-skeletons for β up to 20, we did not find any convincing correlations. However, the following result was obtained.

Finding 9. *$B(\beta)$ ∪ (Batu Pahat, Skudai) = P(26/30), $2.7 \leq \beta \leq 6.4$.*

Compare Fig. 10 and Fig. 6(d).

Finding 10. *If man-made transport links (Rawang, Kuantan), (Seremban, Bandar Melaka) and (Batu Pahat, Skudai) were non-existent and man-made routes (Kajang, Kuantan) and (Kluang, Skudai) built the Malaysian expressways graph would be the minimum spanning grown from Kuala Lumpur.*

The above results from direct comparison of **H** (Fig. 7(a)) and spanning trees (Fig. 9).

Finding 11. *Let L be intersection of proximity graphs with the expressway graph L = RNG ∩ H = GG ∩ H = MST(KL) ∩ H then P(25/30) ∈ L.*

Fig. 10. β-skeletons **B**(β) constructed on **U**, $2.7 \leq \beta \leq 6.4$.

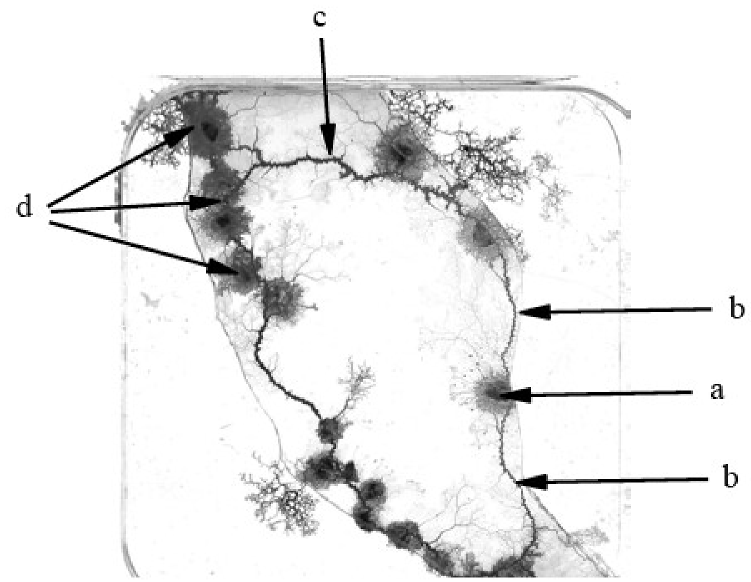


Fig. 11. Recongurationin response to contaminaton. Image is recorded 24 h after contamination. (a) Epicentre of contamination (b) Abandoned transport links (c) Hypertrophied transport links (d) Increase of exploratory activity.

The finding announces the amazing fact that intersections of the expressway graph with proximity graphs are the same. Moreover, this 'intersection graph' is a subgraph of the strong Physarum graph. In other words, the intersection of the expressway graph with proximity graphs is represented by protoplasmic tubes in over 83% of laboratory experiments.

VI. Imitating Response to Disaster

To study reaction of Physarum-grown transport networks on major disasters, we placed crystals of sodium chloride in the approximate positions of Kuantan as shown in Fig. 11(a). Sodium chloride is a strong repellent for *P. polycephalum* [24]. The salt diffuses in the substrate outwards its original application site, the epicentre of disaster. It can therefore imitate radioactive and/or chemical pollution and subsequent disturbance spreading along Malaysian transport networks. Patterns of responses recorded in laboratory experiments are uniform and repeatable. Transport link in domains affected by contamination are destroyed and abandoned. These links are visible as whitish protoplasmic tubes as shown in Fig. 11b. Parts of the transport network positioned far away from the epicentre of contamination becomes hypertrophied, as shown in Fig. 11c due to increase of exploratory activity in the urban areas not affected by contamination, as shown in Fig. 11d. Based on the experiments with slime we can propose the following scenario would develop.

Finding 12. *If epicentre of contaminations is located in Kuantan and speed of propagating contamination is about 100 miles per 24 h transport functionality will be significantly diminished in X14, X3, X63 roads, substantial increase of traffic observed between Kota Bahru and Alor Star, Sungai*

Petani and Kulim areas; significant increase in migration and economic activity would be also observed in Kedah and north Perak and Kelantan states.

VII. Conclusion

In laboratory experiments, we found that protoplasmic networks constructed by slime mould *P. polycephalum* mainly consist of linear chains spanning urban areas along the costal lines. We demonstrated that the slime mould approximates almost all edges of the expressway graph. Only two of 19 transport links are never represented by protoplasmic tubes: (Rawang – Port Dickson) and (Seremban – Bandar Melaka). With regards to particular transports routes, we found that chains of man-made expressways (Alor Star – Port Dickson) and (Bandar Melaka – Pasir Gudang) are imitated by the slime mould in over half of laboratory experiments. Chains of man-made federal roads (Kuantan – Kota Bahru), and expressways (Alor Star – Ipoh), (Bandar Melaka – Skudai) and (Rawang – Port Dickson) are approximated by the slime mould *P. polycephalum* in 80% of experimental trials. In experiments with slime mould we found that structure of Malaysian expressways network is biological from *P. polycephalum*'s point of view. Is it optimal and common-sense logical? Indeed. If man-made transport links (Rawang, Kuantan), (Seremban, Bandar Melaka) and (Batu Pahat, Skudai) were nonexistent and man-made routes (Kajang, Kuantan) and (Kluang, Skudai) built the Malaysian expressways graph would be the minimum spanning grown from Kuala Lumpur. We also experimentally found that if a very large-scale contamination occurs with epicentre in Kuantan, then substantial increase of traffic will be observed along Kota Bahru to Alor Star and Sungai Petani to Kulim routes, as well as substantial increase in migration and economic development in Kedah, north Perak and Kelantan states.

Acknowledgment

This work is supported by the Fundamental Research Grant Scheme (FRGS/1/2012/TK06/MMU/03/7).

References

[1] Adamatzky, A. and Holland, O., Reaction-diffusion and ant-based load balancing of communication networks. *Kybernetes*, 31 (2002), 667–681.

[2] Adamatzky, A., De Lacy Costello, B. and Asai T., *Reaction-Diffusion Computers*, Elsevier, 2005.

[3] Stephenson, S. L. and Stempen, H., *Myxomycetes: A Handbook of Slime Molds*, Timber Press, 2000.

[4] Nakagaki, T., Yamada, H. and Ueda, T., Interaction between cell shape and contraction pattern in the physarum plasmodium. *Biophysical Chemistry*, 84 (2000), 195–204.

[5] Nakagaki, T., Yamada, H., and Toth, A., Path finding by tube morphogenesis in an amoeboid organism. *Biophysical Chemistry*, 92 (2001), 47–52.

[6] Adamatzky, A., *Physarum Machines: Making Computers from Slime Mould*, World Scientific, 2010.

[7] Shirakawa, T., Adamatzky, A., Gunji, Y.-P. and Miyake, Y., On simultaneous construction of voronoi diagram and delaunay triangulation by physarum polycephalum. *Int. J. Bifurcation and Chaos*, 9 (2009), 3109–3117.

[8] Adamatzky, A., *Slime Mould Logical Gates: Exploring Ballistic Approach*, 2010.

[9] Tsuda, S., Aono, M. and Gunji, Y.-P., Robust and emergent physarum logical computing. *Biosystems*, 73 (2004), 45–55.

[10] Schumann, A. and Adamatzky, A., Physarum Spatial Logic. *Proc. 1th Int. Symp. on Symbolic and Numeric Algorithms for Scientific Computing*. Timisoara, Romania, 2009.

[11] Adamatzky, A. From Reaction-Diffusion to Physarum Computing. *Invited Talk at Los Alamos Lab Workshop "Unconventional Computing: Quo Vadis?"*. Santa Fe, NM, 2007.

[12] Adamatzky, A., Ilachinski, A., Slime mold imitates the United States Interstate System, *Complex System*, 21(2012), 1-20.

[13] Adamatzky, A. and Schubert, T., Schlauschleimer in Reichsautobahnen: Slime mould imitates motorway network in Germany, *Kybernetes*, 41(2012), Issue 7/8, 1050-1071.

[14] Adamatzky, A. and Jones, J., Road planning with slime mould: if physarum built motorways it would route M6/M74 through Newcastle. *Int J Bifurcaton and Chaos*, 20 (2010).

[15] Adamatzky, A., Lees, M., Sloot, P., Bio-development of motorway network in the Netherlands: A slime mould approach. *Advances in Complex Systems*, 16(2013), Nos. 2 & 3.

[16] Adamatzky, A. and Kayem, A., Biological evaluation of Trans-African highways, *The European Physical Journal Special Topics*, 215 (2013), 49-59.

[17] Adamatzky, A., Yang, X.S., Zhao, Y.X., Slime mould imitates transport networks in China, *International Journal of Intelligent Computing and Cybernetics*, 6(2013), Issue 3, 232-251.

[18] Adamatzky, A., Martinez, G. J., Chapa-Vergara, S. V., Asomoza-Palacio, R., Stephens, C. R., Approximating mexican highways with slime mould. *Natural Computing*, 10 (2011), 1195–1214.

[19] Adamatzky, A. and Prokopenko, M., Slime mould evaluation of Australian motorways. *Int J Parallel Emergent Distributed Systems*, 27(2012), No. 4, 275-295.

[20] Gabriel, K. R. and Sokal, R. R., A new statistical approach to geographic variation analysis. *Systematic Zoology*, 18 (1969), 259–278.

[21] Matula, D. W. and Sokal, R. R., Properties of gabriel graphs relevant to geographical variation research and the clustering of points in the same plane. *Geographical Analysis*, 12 (1984), 205–222.

[22] Toussaint, G. T., The relative neighborhood graph of a finite planar set. *Pattern Recognition*, 12 (1980), 261–268.

[23] Nesetril, J., Milkova, E., Nesetrilova, H. and Otakar, B., On minimum spanning tree problem. *Discrete Mathematics*, 233 (2001), 3–36.

[24] Jaromczyk, J. W. and Toussaint G. T., Relative neighborhood graphs and their relatives. *Proc. IEEE*, 80 (1992), 1502–1517.

APPENDIX: PHYSARUM GRAPHS FOR ALL VALUES OF θ

$\theta = \frac{1}{30}$

$\theta = \frac{2}{30}$

$\theta = \frac{3}{30}$

$\theta = \frac{4}{30}, \frac{5}{30}$

$\theta = \frac{6}{30}, \frac{7}{30}$

$\theta = \frac{8}{30}$

$\theta = \frac{9}{30} \cdots \frac{11}{30}$

$\theta = \frac{12}{30}, \frac{13}{30}$

$\theta = \frac{14}{30}, \frac{15}{30}$

$\theta = \frac{16}{30}, \ldots, \frac{19}{30}$

$\theta = \frac{20}{30}, \ldots, \frac{22}{30}$

$\theta = \frac{23}{30}, \frac{24}{30}$

$\theta = \frac{25}{30}$

$\theta = \frac{26}{30}$

$\theta = \frac{27}{30}$

$\theta = \frac{28}{30}$