Spotting emergence in wireless routing protocols

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Abstract: This paper outlines the common characteristics shared by different wireless routing protocols that can be grouped together using the science of emergence. Our objective is to present the conditions under which a system can experience an emergent behaviour, as well as to provide a brief summary of what constitutes such behaviour. Finally, we aim to show that wireless routing protocols satisfy these requirements, thus allowing us to group a number of characteristics shared by different implementations as a set of requirements that define a healthy protocol design.

1. Introduction

In recent years the topic of emergence has been gaining attention from a variety of disciplines ranging from biology to software engineering. Whether it has been a case of understanding the behaviour of ant colonies in their struggle for survival [1], or for consumer websites to have the ability of offering hints to visiting customers depending on their past purchase history, this *new kind of science*[1], even at this early stage, is producing results worth noting.

Since emergence, as a science, can be hosted in so many different subjects, an interpretation of what it stands for comes in many different flavours. Three of the most common such descriptions are included below:

- **Bottom-up systems achieving the same functionality as top-down**

  Systems lacking a central administration authority, which are capable of functioning in the same manner as if one was present. The myth of an ant queen in an ant colony is the perfect example of such a natural system [1].

- **A set of simple rules generating complex behaviour**

  Systems governed by a set of very simple rules, having a complex, non-chaotic behaviour. A number of examples of such an artificial system can be found in [2], where the system defined is a cellular automaton.

- **The sum of the parts being greater then the whole**

  A system solving a problem outside its capacity as that would be defined by the principle of superposition (the whole is the sum of the parts) widely used in physics. An example of this can be found in the organisation of the cemetery in an ant colony [3].

The above three interpretations of such phenomena briefly summarise the distinct behaviour that allows us to construe a system as one that hosts or experiences an emergent behaviour. Consequently, the system under investigation achieves a state (as with each description above) that it would not be able to reach otherwise. The question arises as to what systems and under what conditions can we introduce such behaviour to a system, thus exploiting any of the above advantages.

Having labelled some of the advantages that emergence offers, we aim to introduce the necessary conditions required for the existence of such behaviour in a system. Furthermore, we seek to identify such criteria in wireless routing protocols concentrating in the most dynamic network topology, that of the Mobile Ad-hoc Network (MANET), where an information exchange network is formed as a collection of wireless mobile nodes that dynamically change location. Finally, we attempt to identify the potential advantages that emergence might be able to present in wireless routing techniques.

2. Requirements for emergent behaviour

In this section we aim to clearly define the specific requirements that enable for a system to experience an emergent behaviour. As our starting point, we assume the existence of a system comprising of a number of interacting elements, where each element can be uniquely identifiable as part of a greater set or sub-process.

[1] Title used by Stephen Wolfram in his new book [2] on cellular automata, which extensively describes the surfacing of complex system behaviour, spawning from a set of very simple rules governing the system.

Furthermore, we presuppose the system to have an objective that has been defined relative to its input and output from the environment. This brief description, illustrated in figure 1, represents a generalised view of any engineering system and forms the basis of our discussion.

As a starting point in such a system, the element of control is something that should only occur on the local level of elements and not on the global level of the system. If that were not the case, then the presence of a system administrator would be a feasible option that could account for all actions of individual elements. The problem rising from this scenario is that in certain systems it is impossible for a central figure of authority to exist, manage and account for the overall system behaviour. An example of this can be found in wireless networks today and more specifically in the Mobile Ad-hoc Network (MANET) where the communication network is formed as a collection of wireless mobile nodes [4]:

"Even if such services where assumed, their availability would not be guaranteed, either due to the dynamically changing topology that could easily result in a portioned network, or due to congested links to the node acting as server."

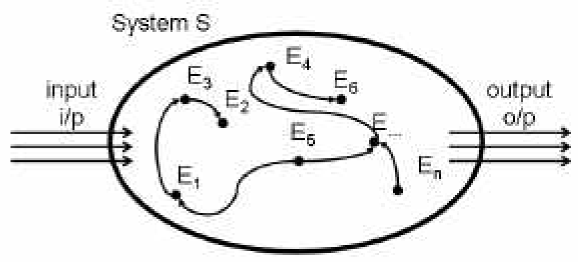

Figure 1: An abstract description of a system S, having a number of interacting elements E. The system is receiving an input from the environment and also producing an output.

Consequently, there exist a number of systems, where the presence of a single entity acting as a central control administrator is virtually impossible, leading us to seek alternatives to such a top-down system approach.

The process of allowing specific freedoms to elements in our system is not one that should be done at random, but whilst keeping in mind the objective of the system with regards to the input and output. Consequently, demolishing a main figure of control implies upgrading each element to a state of awareness of its surroundings. This leads to the following requirements for emergence to occur.

- **Allow for equality to spawn the system**

  Even though the presence of each element in the system is justified by the different role that it serves in it, all elements should be allowed to interact using exactly the same principles, thus creating a flat architecture where each decision or statement is treated equally by every other neighbouring element.

- **Encourage all feedback, both positive and negative**

  In this communication process, some of the feedback generated by specific elements might have malicious intent jeopardising the functionality of the system. Even in these cases such feedback should be allowed to propagate, but, based on a model of inertia, not acted upon. As a result, each element will be able to conclude for itself on specific elements and classify them as malicious or useful to them.

- **Make sure the system can serve its purpose**

  It is very important not to forget that the system exists for achieving a well defined goal or serving a specific purpose. Interactions between nodes should be encouraged, but not dominated by internal information and views on other parts of the system. Furthermore, an ill defined problem can lead to generalisations that are too great. This would result in a universal adaptive plan [5] that would be too vast to manage. As a result, the exhaustive element interaction would be overwhelming, compared to any relative success.

- **Pay attention to your neighbours**

  In order for the system to function in a proper manner, each element must be willing to put in the energy (usually reflected in power consumption) to pay attention to what neighbouring elements are doing. The system will fail if elements, upon receiving information from adjacent elements regarding performance, simply ignore it or choose to adapt a simple premeditated strategy regardless of the state of the system.

From the above four requirements that enable a system to exhibit emergent behaviour, allowing an equal environment of interaction is a rule that has been imposed in MANETs as a consequence of not having a direct connection to every node. In the following section, we will attempt to quantify if the complete set of requirements can be met for a dynamic communication network, thus reaching the conclusion of whether or not emergence can exist in a complex artificial system, such as that defined by a MANET.

3. Emergence in wireless routing protocols

In the classification of wireless networking technologies for mobile users, the MANET, consisting of a dynamic set of nodes, each acting without a central administrator or a predefined infrastructure for the network, poses as one of the most dynamic systems for exchanging information. The idea behind a MANET, also referred to as *infrastructureless networking* [6], relies on individual devices establishing a dynamic topology capable of handling routing on demand between them. As a result, the network becomes an abstract representation of the multihop routing paths each node selects to utilise at any one time.

In this environment, the protocol of communication plays a vital role on the stability of the network. With no higher figure of command present, the devices on the network need to rely on one another for a successful data flow. Routing protocols, used for ad-hoc networks fall under two main categories [7]

- **Table-driven**

  Attempt to keep a consistent table of routing information from each node to every other node on the network. This is done by each node storing routing information collected from the network and propagating this information to every other node, in order to keep a consistent view with every other node. Two of the most popular implementations are Destination-Sequence Distance Vector Routing (DSDV) described in [8] and the Wireless Routing Protocol (WRP) [9].

- **Source-initiated on-demand driven**

  Routes are created on demand by a source node wanting to exchange information with a specified destination. In this approach, the source node initiates a route discovery process within the network, which is complete once a route is found or all the possible permutations are exhausted. Examples of such implementations include the Ad-hoc On-Demand Distance Vector Routing (AODV) protocol [10], as well as the Dynamic Source Routing (DSR) protocol [11].

Both the above categories of routing protocols satisfy the first requirement regarding equality on the network. In the table driven scenario, each host collects information regarding its experience in routing traffic on the network, which is later shared with every other host. For the source-initiated on-demand driven protocols, every host has the right to launch a route discovery process, expecting the compliance and assistance of other devices on the network. This enables us to conclude that, overall, wireless routing protocols encourage equality between nodes on the network[2].

With regard to the second requirement, encouraging feedback between nodes poses as a time dependant process associated with paying attention to your neighbours. The functionality of the wireless routing protocol (regardless of it being table-driven or source-initiated on-demand driven) depends on feedback from other nodes. In classifying positive and negative feedback in a wireless network, we can argue that positive feedback stems from what we would normally classify as healthy nodes, exchanging information with other nodes on a regular basis, whilst negative feedback is the lack of such communications taking place. Based on this classification, each node has the ability to distinguish between neighbouring nodes in terms of the feedback (i.e. the presence or absence of data exchange) that they offer.

One of the most important aspects of wireless routing protocols is the overhead of data they introduce to network traffic. A node can spend most of its time exchanging information that enables it to find the optimal path to every other node on the network, without actually utilising that path for any data exchange. This is how the third requirement, stating that the system under inspection should always have the ability to serve its initial purpose, surfaces. In the process of information being exchanged in a mobile ad-hoc environment, it is very important to avoid the pitfall of consuming all available bandwidth on issues connected with how to communicate, without actually communicating. Thus, no matter how complex our decision making process might be, we should never neglect the initial purpose of the system, which in our case is the exchange of information.

Finally, there is the issue of paying attention to your neighbours. A specific node must be interested on information regarding neighbouring nodes. In the table-driven scenario, with the exception of CGSR [12], this is something that we encounter through *hello messages* being sent to neighbouring nodes. For both DSDV and WRP, a node has the ability to indicate its presence on the network via broadcasting such messages to neighbouring nodes. On the other hand, in CGSR due to the presence of clusters, paying attention to your

[2] One potential exception to this rule is a descendant of DSDV, namely Clustered Gateway Switch Routing (CGSR). Even though CGSR encourages a hierarchical routing philosophy via clusters [12], equality is still present but on two different levels; all nodes within a specific cluster have the same rights and also all nodes acting as cluster heads have the same rights. Moreover, cluster heads as well as clusters can vary in time.

neighbours is something that is achieved through the assigned cluster head. In source-initiated on-demand driven protocols, a node upon wanting to exchange information launches a route discovery process within the network, requiring the attention of not only the destination, but also other neighbouring nodes. This is achieved by sending a specific type of packet, referred to as route request (RREQ) packet in AODV [10], on which propagation towards the destination node is recorded. Consequently, in both types of routing protocols paying attention to your neighbouring nodes comes as a prerequisite of the protocol functionality.

4. Conclusions

This paper has provided an overview of the conditions under which functioning systems consisting of a number of elements can experience emergent behaviour that can lead to bottom up architectures lacking a central administration authority, or complex behaviour stemming from a set of simple rules.

Furthermore, we have shown that in wireless networks, particularly in MANETs where it is virtually impossible to have a central administrator node [4], the four requirements leading to a system experiencing emergent behaviour can be accounted for by most routing protocols. Furthermore, the requirements for an emergent system form the basis of a proper exchange of information, lacking a central administration authority. This has enabled us to group together a number of common characteristics that routing protocols share and further provide justification of the need for specific features as a guarantee of correct functionality.

From the above four requirements, an interesting point that could also pose as a great disadvantage in further utilising emergence in wireless routing protocols, is the aspect of having to upgrade in terms of hardware previously simple elements so that to account for the intensity of decision making that would only be needed for the correct behaviour of a top-down architecture. Since our main area of concern is the MANET, accounting for that capacity on the lower levels is something that we can afford, based on Moore's law of exponential growth for computational capacity. As a level of comparison, the average mobile phone today, has the computational ability of a desktop ten years ago; consequently, emergence is something that we can afford in the wireless medium.

Finally, having grouped a number of characteristics of routing protocols under the same umbrella of emergence, part of future research would involve the development of a purely emergent protocol for route establishment in wireless administration-lacking networks, combining the selectively chosen good aspects of both table-driven and source-initiated on-demand driven protocols.

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