Self-Adaptive and Mobility-Aware Path Selection in Mobile Ad-Hoc Networks

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ABSTRACT

In this paper we propose a protocol that uses mobility information and attractor-selection to effectively and adaptively establish stable communication in mobile ad hoc networks (MANETs). The aim of this approach is to not only establish stable durable communication paths between mobile entities, but also to create a resilient network which can quickly recover from unexpected changes in the network topology. In the proposed protocol, links will have longer lifetimes and break less frequently (as a result of mobility) and the established network will be more stable and resilient to sudden changes in network topology.

Keywords

Self-adaptive networks, self-organizing networks, mobility-aware routing

1. INTRODUCTION

Due to the perpetual increase in the level of reliance and usage of ubiquitous network services, future information network technologies are expected to provide a higher degree of interaction to the user's demands. We believe that such ambient infrastructures would benefit from mimicking nature's own mechanisms to provide a transparent and stable communication platform, which is self-adaptive and self-organizing, and does not rely on centralized control.

Self-organization in mobile ad hoc networks presents the next wave of enhancing rapid and resilient setup of an ad hoc network. In [1], the *mobile ad-hoc routing with attractor-selection* (MARAS) was introduced which used the biologically inspired attractor-selection in its self-organizing and self-adaptive mechanism. However, in [1] the network nodes were assumed to be stationary and topology changes were induced only upon an on/off activity pattern of the nodes.

In order to consider the effects of mobility in the network, a mobility metric also needs to be considered in the routing protocol. In [2], the *multipath Doppler routing* (MUDOR) was introduced which effectively seeks stable paths for routing in a mobile network. In MUDOR, routing is based on a mobility metric based on the Doppler shift subjected to packets for estimating the stability of links and paths.

In this paper we propose a routing protocol that builds upon MUDOR by incorporating the attractor-selection method used in MARAS, in order to establish durable paths that have longer lifetimes and do not frequently break in an environment consisting of highly mobile nodes, whilst providing adaptability to good selections of paths. The approach is capable of adapting good paths which may not otherwise be realized by traditional "best" path selection, however will be realized over time. The proposed protocol is therefore primarily aimed at highly mobile ad hoc networks, which are pseudo-linear in nature. Such applications of the protocol may range from aeronautical [2] to vehicular ad hoc networks [3], trains, ships and so on, and we can thus assume that the nodes are not limited by power or energy consumption restrictions. In such scenarios the stability of links also become a crucial factor, as due to the high mobility of nodes, established communication paths may be short-lived if mobility is not considered in the routing protocol.

This paper is organized as follows. Section 2 describes the background and model related to our proposal. Section 3 introduces the proposed protocol. This is followed by performance evaluation in Section 4, and finally conclusion in Section 5.

2. BACKGROUND AND MODEL

Biologically inspired methods bear the inherent characteristics of a high degree of robustness [4,5] and the ability to dynamically adapt to changing environments. Therefore, the application of mechanisms from biology seems to be highly promising especially in the presence of sudden changes in an unstable and unknown network topology. In this section we will briefly summarize the biological background and mathematical model of the attractor-selection dynamics, which can be regarded as a

Bionetics'08, November 25-28, 2008, Hyogo, Japan.

self-adaptive control mechanism driven by the intrinsic and ambient noise of the network. We believe that in order to achieve the highest level of transparency in a naturalistic way, is to mirror or at the very least be inspired by nature's inherent mechanisms. Fundamentally, at a higher abstract level, the proposed mechanisms constitute a small part of an ambient information society, where the artificial intelligence in the environment (consisting of sensors, self-aware systems, and other electronics and computers) readily provide services to individuals by being aware, and able to respond to environmental needs.

2.1 Attractor-Selection Mechanism

This paper considers the heuristic dynamical mechanism of attractor-selection, which self-adaptively selects one solution among a set of candidates utilizing the inherent noise in the system [6,7]. The selection follows the system dynamics embedded in a set of differential equations and the selection itself is performed without explicit rules, as each node simply follows the same dynamical pattern. Thus, it seems well suited for application in ambient network environments.

The basic mechanism of attractor-selection was introduced by Kashiwagi et al. [6], who experimentally studied the effects of two mutually inhibitory operons in E. Coli cells reacting to the lack of a nutrient in their exposed medium. A mathematical model was proposed in [6], which serves as the basis of our proposed mechanism. The general form of a system of N stochastic differential equations can be given as in (1).

$$\frac{dx_i}{dt} = f_i(x_1,\ldots,x_N)\alpha + \eta_i \quad i = 1,\ldots,N \qquad (1)$$

The basic dynamic behavior can be described as follows. The system state contains all x_i and is derived from the concentrations of the messenger RNA (mRNA) molecules in the original model. The functions f_i define the attractors to which the dynamic orbit of the system will eventually converge in spite of the existence of an inherent noise term η_i. A key term is α, which is a non-negative function representing the cell's growth rate and is related to its activity. Essentially, this function influences the actual selection by switching between two modes of operation. In the first case, if $\alpha > 0$ the dynamics of (1) follows a rather deterministic way and the fluctuations introduced by η_i will not influence the convergence to an attractor, under the condition that the noise amplitude is sufficiently small. On the other hand, when α approaches 0, the dynamics of (1) is entirely governed by η_i leading to a random walk in the phase space.

2.2 Definition of Attractors and Activity

In the previous section we briefly summarized the underlying concept of attractor-selection. Now, we will provide a more detailed formulation of the specific equations we use in this paper.

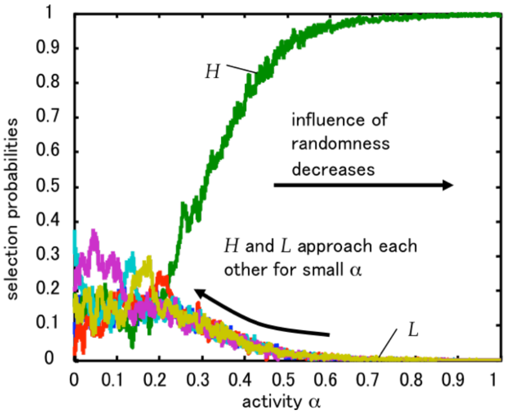

Fig. 1: Relationship between activity and randomness

2.2.1 Formulation of Attractors

Let us assume that we have a given set of paths $\mathbf{P} = \{p_1,\ldots,p_N\}$, obtained by the method we will later describe in Section 3. We will use the same formulation for the attractors as in [1], which is basically an extension of [6] to an arbitrary dimension, and we will in the following briefly summarize the underlying attractor model. Further alternative ways of defining suitable attractors are discussed in [8]. Consider a set of stochastic differential equations as:

$$\frac{dx_i}{dt} = \frac{s(\alpha)}{1 + x_{\max}^2 - x_i^2} - d(\alpha)\, x_i + \eta_i \quad i = 1,\ldots,N \qquad (2)$$

where $s(\alpha) = \alpha(c\,\alpha^k + \tilde{\varphi})$ and $d(\alpha) = \alpha$ are the rates for synthesis and degradation of the state values x_i, and c and k are constants determining the shape of adaptation. Furthermore, let us define their ratio as

$$\varphi(\alpha) = s(\alpha) / d(\alpha) = c\,\alpha^k + \tilde{\varphi}\,.$$

The equation system (2) has N stable attractors of the form $\mathbf{x}^{(j)} = [L,\ldots,L,H,L,\ldots,L]^T$ with a high value H at the j-th index and low values L at all other positions. In [1] it was shown that the high and low values can be given as follows.

$$H = \varphi(\alpha) \qquad L = \frac{1}{2}\left(\sqrt{4 + \varphi(\alpha)^2} - \varphi(\alpha)\right)$$

The term $\tilde{\varphi} = 1/\sqrt{2}$ is a critical point at which $H = L$. An example of the influence of the activity α on the values H and L is illustrated in Fig. 1. Note that when activity becomes large, the influence of randomness decreases, while for small α the high and low values are nearly equal, but there is an increased degree of fluctuation. The resulting values $\mathbf{x}^{(j)}$ is used for selection.

2.2.2 Activity Model

While the attractor description is rather independent of the considered application, the activity must be set to its objectives. Here, we will only briefly discuss the general structure of the activity dynamics, but later in Section 3 we will elaborate on the details by proposing the actual activity function that will be used for the numerical evaluation of this proposal. The generalized dynamics of an activity function can be formulated as follows:

$$\frac{d\alpha}{dt} = \rho\left(\tilde{\alpha} - \alpha\right). \tag{3}$$

In this equation, $\tilde{\alpha}$ is a measured target value and ρ is the rate of adaptation. This value should be chosen smaller than 1 in order to make the system less sensitive to sudden changes due to fluctuations of the measured performance metric. The measured metric $\tilde{\alpha}$ should map the suitability of the current choice of attractor to the environment and be 0 in the case of bad suitability, and greater than 0 when the selection is good. For the sake of simplicity, we can assume that a value of 1 is adopted in the latter case.

3. THE PROPOSED PROTOCOL

The protocol that we propose in this paper is based on the application of data retrieval from a stable path in a mobile network with mobile entities. One or more mobile nodes may provide the requested data in the network. The speed of nodes is high enough to cause a Doppler shift in communication signals [2]. Furthermore, the attractor selection mechanism differs from that of MARAS [1] in that the attractor selection is performed at the requesting node among multiple known complete paths to provision nodes, in oppose to at attractor selection at each intermediate node as in MARAS.

3.1 Mobility Metric: The Doppler Value

The mobility metric proposed for determining “good” links (and ultimately paths) is the *Doppler value* (*DV*) introduced in [2] and is given by

$$DV = \begin{cases} |v| = c\left|\left(\dfrac{f}{f_o} - 1\right)\right| & \text{if } \dfrac{f}{f_o} < 1 \quad \text{for approaching nodes} \\ 2|v| = 2c\left|\left(\dfrac{f}{f_o} - 1\right)\right| & \text{if } \dfrac{f}{f_o} > 1 \quad \text{for receding nodes} \end{cases} \tag{4}$$

where v is the relative velocity between two nodes within range, c is the speed of light, f is the expected (known) frequency of signal/packet, and f_o is the observed frequency of the signal/packet.

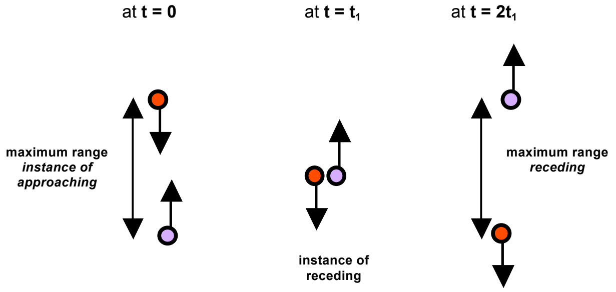

Fig. 2: Two nodes approaching and then receding from each other

From (4) it can be seen that we have chosen a factor of two for receding nodes. The justification for this is that receding nodes are considered half as stable as approaching nodes, since nodes which are approaching would *generally* be within communication range of each other for *twice* as long as receding nodes. The idea behind this lies in the fact that all approaching nodes will eventually recede from each other, however receding nodes will never approach each other. To further illustrate this, consider two nodes at maximum communication range directly approaching each other as in Fig. 2. These nodes will first reach each other and then they begin receding from each other until they reach their maximum communication range before going out of range.

The time taken from maximum range approaching to maximum range receding is *twice* that of the instance of receding to maximum range receding. Hence we use a factor of two for receding nodes to make the Doppler value twice that of the approaching case of the same relative velocity. It should be noted that throughout this paper we assume that all nodes move at constant speed. Furthermore, it is assumed that the nodes’ speed is high enough for the Doppler shift of exchanged packets to be measurable (and hence the Doppler value to be calculated).

3.2 Path Discovery

The algorithm for finding paths, proposed in this paper, follows the MUDOR algorithm [1]. Initially, a node referred to as the requesting node wishes to obtain certain data from any node that can provide that data. Once the requesting node obtains all candidate paths through a route discovery procedure, the selection of the path is performed using the *attractor-selection* method, dubbed as MUDOR-AS. For the sake of comparison, we also implement *random selection,* which randomly selects *one* of the set of paths obtained through the MUDOR procedure. This will be referred to as MUDOR-R. The routing protocol involves two steps. 1) *path discovery*, 2) *path selection*.

In the following, we will describe in detail the processes involved for the nodes participating in the routing protocol. The path discovery procedure is described next.

3.2.1 Requesting Node

The requesting node broadcasts *route request* (RREQ) messages to all *line-of-sight* (LOS) single-hop neighbor nodes, requesting for the "id" representing the requested data.

3.2.2 Receiving Node

We need to distinguish between two kinds of receiving nodes, those that simply forward the request and those that act as servers and have the queried data. In order to take the Doppler value into account, we need to consider the following quantities, related to the Doppler shift subjected to both the RREQ and RREP packets.

The *Packet's Doppler Value* (PDV) is the cost related to the Doppler shift subjected to the whole packet as it travels from the previous node to the current node. The *Packet Header Doppler Value* (PHDV) is the *bottleneck* Doppler value so far on the path. The PHDV is updated at each node, and also on the return path as part of the *route reply* (RREP) packet. The other is the minimum Doppler value for the same identical RREQ stored at each receiving node, termed *Best Doppler Value So Far* (BDVSF). This is used as a discriminator for identical RREQ packets. Only RREQ packets that provide a smaller Doppler value are forwarded, otherwise they are discarded. In addition, each node adds its own address to the packet cache addresses, like the dynamic source routing (DSR) protocol [9] before forwarding the packet. This assists in the non-disjoint path discovery, and allows the requesting node (source node) to choose from a set of stable paths for retrieving data. A pseudo-code description of the Request-Forwarding and the Reply-Forwarding are given as follows.

Request-Forwarding:

```
If PDV > PHDV
  PHDV = PDV
End if
If PHDV < BDVSF
  BDVSF = PHDV
Else
  Drop RREQ
If RREQ not dropped and Node has id
  Produce RREP
Else
  Rebroadcast RREQ: (hopcount = hopcount-1)
End if
```

Reply-Forwarding:

```
If PDV > PHDV
  PHDV = PDV
End if
If Receiving Node is Requesting Node
  Store RREP in table
Else
  Forward RREP to previous node
End if
```

3.3 Path Selection

3.3.1 Using Random Selection (MUDOR-R)

The MUDOR-R (MUDOR-Random) mechanism randomly selects one of the paths obtained at the requesting node, through the MUDOR procedure. Note that these paths are not simply randomly selected possible paths, but are already partially stable due to the nature of the algorithm's tendency to retrieve paths with good Doppler values. New path selection occurs once the current path breaks. Hence the requesting node also performs path discovery at the instance of path break.

3.3.2 Using Attractor-Selection (MUDOR-AS)

The MUDOR-AS (MUDOR Attractor-Selection) variant uses the attractor-selection scheme described in Section 2 to select one of the paths obtained through the MUDOR procedure. Path selection occurs upon current path break. Hence we assume the requesting node has already obtained a set of paths from which it can select one as the next path after the current path breaks (sue to mobility). The route (path) discovery procedure would hence occur at the time (or just before) current path break. The details are as follows. Firstly a random vector with the size of the number of current paths is initialized with random values. The activity at this point is set to zero. Equation (2) then describes the dynamic of the system over time, which tries to find a good solution, when the system converges. Hence there is a virtual "random walk" phase where selection takes place between the obtained paths, until one path selection falls to a high value and the others to a low value. At this point the system has converged, and the high value is selected as the path for routing. Furthermore, the target activity $\tilde{\alpha}$ can be calculated using:

$$\tilde{\alpha} = 1 - \frac{DV_B(s,d)}{DV_{\max}} \tag{5}$$

where DV_B is the maximum DV on the *current* path. From (4) it can be seen that the ideal path would have a DV_B close to zero, giving a value of $\tilde{\alpha}$ close to 1. The worst case would be when DV_B is close to DV_{max} giving a value of $\tilde{\alpha}$ close to 0. DV_{max} is the *maximum possible* Doppler value on *any* path.

$$DV_{\max} = 2\, v_{Rmax} = 2\left(v_{kmax} + v_{lmax}\right) \tag{6}$$

where v_{Rmax} is the maximum possible relative velocity between a pair of nodes on *any* path and v_{kmax} and v_{lmax} are the individual speeds of the two highest speed nodes, *kmax* and *lmax*, in the network and $DV_B(s, d) \leq DV_{max}$. Furthermore, the activity function is given in (7), which mirrors that of (3), and allows the system to adapt to a previously chosen "good" path.

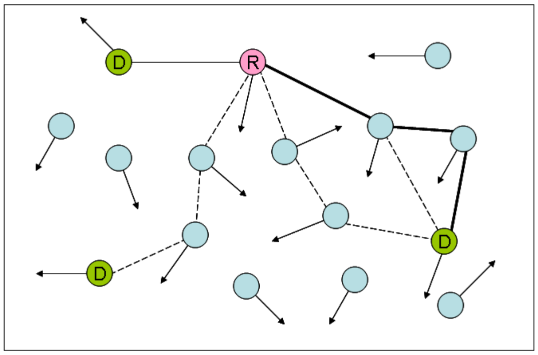

Fig. 3: Application scenario for the proposed protocol

$$\frac{d\alpha}{dt} = \rho\left(1 - \frac{DV_B}{DV_{\max}} - \alpha\right) \tag{7}$$

In a normal system, *kmax* = *lmax* = the highest possible of any node. If all nodes are the same, this value is inherently known by each node. Otherwise this value must be exchanged using a flooding mechanism.

4. PERFORMANCE EVALUATION

In this section we will conduct some simple experimental results through simulation to verify the stability of our proposal. We will first describe the scenario and the assumptions that we use in our simulation and then compare the results obtained for both methods, MUDOR-R and MUDOR-AS, described in the previous section.

4.1 Considered Application Scenario

We assume a mobile network, where nodes are able to obtain data from one or more other nodes. For the initial case we consider a certain percentage *p* of nodes, which cannot provide the requested data. Hence, there are 1 – *p* nodes among all nodes, which can serve as data providing nodes. Fig. 3 shows the application scenario. In the figure, node *R* represents the requesting node and *D* the data providing nodes.

In the figure, there are three *D* (data providing) nodes from which *R* is able to obtain the desired data. The selected path shown in the figure is relatively the most stable path among the four identified paths, as all nodes on the path (including the requesting and data providing nodes) are moving in the same direction as the requesting node. Note that although there is a node *D* only one hop away to the left of node *R* it is not selected since its Doppler value indicates that it is traveling into a different relative direction, thus making this path likely to break in the near future. The mobility model considered is a random waypoint model, which has been well studied in the literature [10].

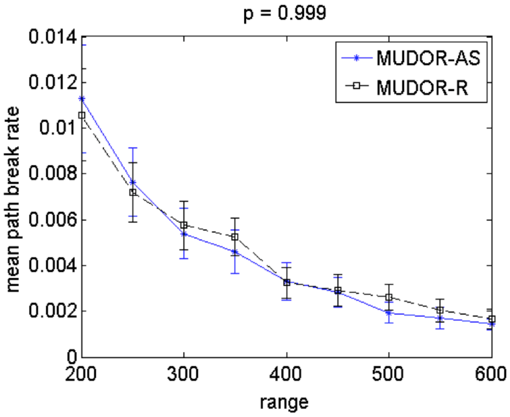

Fig. 4: Results for mean path beak rate, 0.1% data nodes.

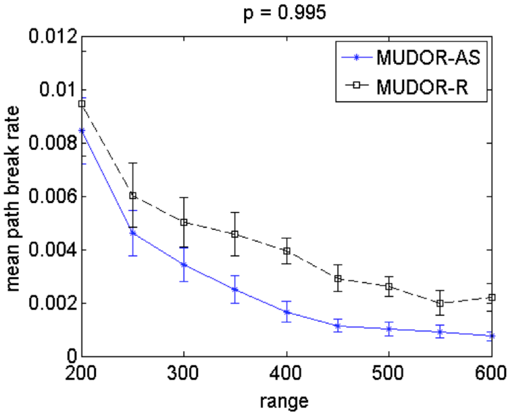

Fig. 5: Results for mean path beak rate, 0.5% data nodes.

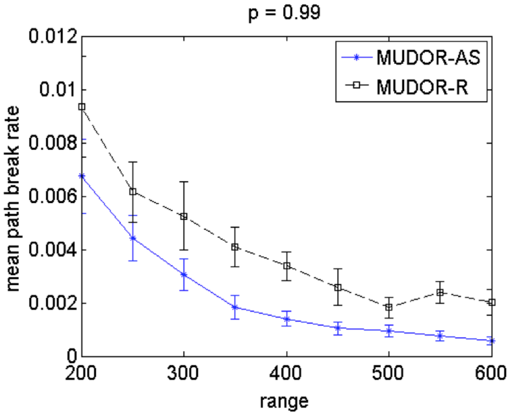

Fig. 6: Results for mean path beak rate, 1.0% data nodes.

4.2 Simulation Results

The following simulations involve 5000 mobile nodes across a platform of 3000 by 3000 space units. Nodes are given a high speed of 14 units/time unit. Each simulation is run for 10000 time units for 20 different scenario cases. In order to investigate the performance of our proposal as selection scheme for paths, we varied the communication range of each node between 200 and 600 units and considered 3 different values of p = 0.999, 0.995, and 0.99 of non-data providing nodes among all nodes. We also assume that all data-providing nodes that receive a RREQ message return a RREP message back to the requesting node. There is one requesting node, which will be requesting data from the data-providing nodes in the network. We also show the 95% confidence intervals of the mean values obtained from these 20 simulation runs.

Figs. 4-6 show the results for the mean rate of path breaks with varying transmission range, when 0.1%, 0.5%, and 1.0% of the total nodes possess the requested data, respectively. The general trend for both simulated algorithms is that fewer path breaks occur as the transmission range increases. This general trend is caused by two reasons. Firstly, as the range increases, there is also an increase in one-hop neighbors and consequently more selection choices, leading to a higher probability of selecting more stable paths. Another reason is that an increasing range would reduce the probability and frequency of nodes moving out of line of sight of each other, which would cause path breaks. In Fig. 4, the performance for MUDOR-AS and MUDOR-R are nearly equal, however MUDOR-AS produces slightly fewer path breaks than MUDOR-R for higher ranges. The result of this close similarity in performance is due to the limited number of paths obtained (resulting in fewer selection choices) since there is only a very small number of nodes providing the desired data. In Figs. 5 and 6, there are higher probabilities of nodes possessing the requested data, and hence more selection choices. This effectively results in a better stable path selection by MUDOR-AS, resulting in lower mean path break rate in comparison to MUDOR-R. Hence, MUDOR-AS is able to obtain a better path selection than that of MUDOR-R regardless of the number of obtained paths, however the performance of MUDOR-AS becomes more apparent for both higher ranges and higher number of available paths for selection.

5. CONCLUSIONS

In this paper we proposed an extension to MUDOR [1] to envelop a biologically inspired approach for the purpose of introducing adaptability and resilience into the protocol. Simulation results show the general effectiveness of the approach in obtaining stable paths in the network when compared to selection using a random approach. However, as we use the paths provided by the MUDOR baseline mechanism, the random variant MUDOR-R already uses rather stable candidates for selection, which explains why in some cases the results do not adversely differ from the attractor-selection scheme.

In the future we wish to study the impact of the parameters in greater details as well as compare MUDOR-AS to a random selection, which does not take the path pre-selection by MUDOR into account. We expect that MUDOR-AS will greatly outperform the random selection in that case. Another issue of interest is to see how well MUDOR-AS can adapt to repeating mobility patterns. Due to its higher adaptability, we expect more promising results than for the random waypoint mobility model.

6. ACKNOWLEDGMENTS

This research was supported in part by "Global COE (Centers of Excellence) Program" of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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