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Distributed multipath routing with packet allocation based on the attractor renewal model

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Abstract—Information communication network is rapidly growing recently. In order to reduce control overhead and realize efficient routing, distributed routing protocols attract much attention. One of these protocols is the attractor selection model that has been proposed inspired from a mechanism of gene expression in living cells. Distributed routing protocols including the attractor selection model, however, often fail to properly respond to traffic changes that occur on non-used paths because these protocols cannot aware status of network beyond their local scope. In order to overcome the problem, we propose a distributed multipath routing protocol based on "attractor renewal model" that is an extension of the attractor selection model. In order to show validity of the proposed model, we perform network simulation where traffic condition changes in time. Results show that the proposed protocol surely rearranges allocation of packets depending on traffic condition beyond local scope of each node.

1. Introduction

Centralized routing protocols that requires information of whole network to operate now starts to face difficulties of robust and smooth operation due to increase in communication overhead accompanied with recent rapid growth of size and diversity of information communication networks [1]. In order to reduce communication overhead and realize robust and smooth routing that can be applicable even to much larger network, distributed and adaptive routing protocols in which operation on each node requires only local information of network such as communication delay on a few routes through the node attracts much attention recently.

These adaptive and distributed protocols include methods proposed inspired from adaptive nature of biological systems [3]- [7]. Biological systems often seem to have ability to promptly respond to environmental change even though the change is suddenly occurred. Moreover, these abilities often require only limited knowledge of their environment. Whereas these responses are not always optimal, quick, and often stochastic, responses of biological systems allow animals to survive in harsh environment with severe battles for existence.

The routing protocol based on the Adaptive Response Attractor Selection model (ARAS) is one of these biologically inspired protocols. ARAS was originally proposed to describe nonlinear dynamics of gene expression of a cell, E. coli. If the cell is in an environment with insufficient nutrient, gene expression network of the cell about metabotropic process changes itself to synthesize the depleted nutrient adaptively. Phase space of the dynamics has stable attractors corresponding to different nutrients and the adaptive dynamics is well described by autonomous selection of one of these attractors. Intriguingly, the dynamics is not deterministic. Rather, biological experiments and theoretical analysis of the phenomena reports that the process is stochastic and underlying fluctuation plays an essential role to adaptive attractor selection, which allows the network to suitably respond to even sudden change of environment [2].

Proposed routing protocol based on the ARAS assigns each attractor in phase space to a possible choice of next hop nodes on each node. Each node on the network calculates the stochastic dynamical equation independently. Depending on measured communication delay of a selected attractor, i.e. a selected next hop node, relative strength of fluctuation to deterministic force attracting the system to an attractor in the dynamical system changes adaptively. Strength of fluctuation increases, if the delay is large, and strong fluctuation forces the system to exit from the current attractor. On the contrary, if delay of the current selection decreases, relative strength of fluctuation decreases, which allows the system stays the current selection [5], [6].

Because the routing protocol can work without information of the whole network such as topology or connectivity of whole network or average delays on all pairs on nodes, the protocol largely reduces communication overhead comparing with centralized routing protocols as OSPF (Open Shortest Path First). This advantage allows us to set duty cycle of the protocol short and to realize packet routing that promptly reacts to rapid change of environment such as sudden change of traffic on the network.

The lack of global information, however, can be a significant drawback of the distributed routing protocol. Because attractor selection, or route selection, on each node is performed only based on communication delay along currently attractor, i.e. currently chosen next hop node, the protocol cannot aware change of communication condition along currently non-used next hop node. Even though background traffic along a next-hop node decreases suddenly, for example, and communication delay along the next-hop node decreases largely, the ARAS cannot aware of appearance of the better route if ARAS does not select the route now. Due to random nature of the ARAS, it is still possible for ARAS to accidently find the better route. The response time, however, may not be sufficiently short.

In order to overcome the problem of the ARAS, here, we propose a distributed multipath routing protocol in which position of an attractor adaptively and continuously renewed based measured communication delay. On the contrary to the ARAS, the proposed protocol does not select a next-hop node. Rather, it adaptively changes "weights" of possible next-hop nodes based on position of an attractor and use these nodes with a ratio that proportional to the weight when it sends a packet.

In this paper, we first introduce the ARAS in the next section, and propose our routing protocol in section 3. We confirm validity of the proposed model using numerical simulation about queuing network in section 4. Conclusion is given in the last section.

2. Adaptive Response Attractor Selection model

2.1. Attractor selection model

Attractor selection model [2] is a nonlinear mathematical model describe the mechanism of E. coli cells adapt to surrounding nutrient environment by changing gene expression according to metabolic network, and synthesize lacking nutrient. In [2], genes which synthesize two different nutrients suppress the other gene expression and reach a stable state, called attractor, in which genes synthesize one of nutrients stably. The following equation describes concentrations of mRNA $\vec{m} = (m_1, m_2)$ corresponding to nutrient synthesis.

$$\frac{dm_1}{dt} = \frac{S(\alpha)}{1 + m_2^2} - D(\alpha)m_1 + \eta_1 \quad (1)$$

$$\frac{dm_2}{dt} = \frac{S(\alpha)}{1 + m_1^2} - D(\alpha)m_2 + \eta_2. \quad (2)$$

Here, α is activity of the cell, which represents goodness of current selection. $S(\alpha) = \frac{6\alpha}{2+\alpha}$ and $D(\alpha) = \alpha$ represent functions of gene synthesis and degradation respectively, η_1, η_2 are fluctuation of gene expression, which is represented white Gaussian noise.

Figure 1 conceptually illustrates behavior of the attractor selection model to environmental change. When activity is high, potential of $\vec{m}$ is enough deep to E. coli stays stably in the current attractor even under fluctuation. When activity becomes low, potential of $\vec{m}$ becomes flat. Relative strength of fluctuation of gene expression becomes larger, and the system starts to exit from the current attractor to explore new attractor that provides higher activity. If the system succesfully finds a good attractor with high activity, depth of potential of $\vec{m}$ increases again.

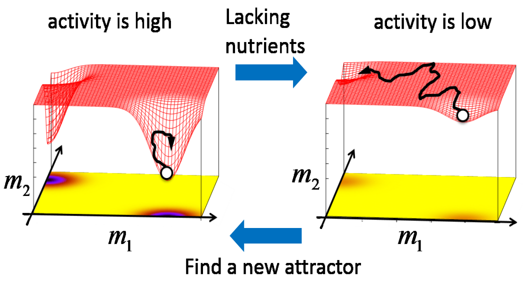

Figure 1: In attractor selection model, cells try to find a stable state among attoractor by fluctuation if α becomes low

2.2. Routing with Attractor selection model

In [5], attractor selection model is extended to M-dementional dynamical systems in order to apply M candidates of next-hop.

$$\frac{dm_i}{dt} = \frac{s(\alpha)}{1 + m_{max}^2 - m_i^2} - d(\alpha)m_i + \eta_i. \quad (3)$$

M is the number of candidates next hops of a node where the routing protocol is performed, $\alpha(0 \leq \alpha \leq 1)$ is the activity that represents goodness of current path defined as,

$$\alpha(h) = \frac{min_{(0 \leq k \leq W-1)}[w(h-k)]}{w(h)}, \quad (4)$$

where $w(h)$ represents communication delay at time h, W is a number of memory of past communication delay of used path. $m_{max} = max(m_1 ... m_M)$, $s(\alpha) = \alpha(\beta\alpha^\gamma + \phi^*)$, $d(\alpha) = \alpha$, $\phi^* = \frac{1}{\sqrt{2}}$, and η_i is a noise term. Equation (3) has M attractors, where one of $\vec{m}$, e.g. $m_j, j = (1, ...M)$, takes a high value and the others take a low value. Each node identically calculates α and m_i for all destination router.

Because the activity is defined as ratio between delay of current step (h) and the minimum delay over past k steps, it decreases when communication delay get worse, which increases relative strength of the noise term and forces the protocol to find a better path. Note that if delay along currently selected path keeps constant value, the value of the activity continues to keep unity, which implies that the router continues to select the same path even though other better paths appear in currently non-selected paths.

2.3. Routing with Attractor renewal model

In order to solve the problem of limited scope and allow routers change their route to better paths even though these paths are not the currently used path, we propose a multipath routing protocol by extending attractor selection model. The routing protocol controls the ratio of packet allocation according to communication delay of path for effective use of network rather than select one route. We use $\vec{m}$ to represent the ratio of packet allocation to next-hop node as the ratio of the ith node p_i is proportional with m_i. This means that position of attractor in phase space corresponds to ratio of packet allocation, and in order to control allocation adaptively, we need to change position of the attractor flexibly with reflecting goodness of these paths. As the control mechanism, we propose attractor renewal model, in which the position of attractor in phase space is updated with reflecting communication delay measured by using these routes.

We define function $f(d_i)$ that will be used to associate ratio of packet allocation to the ith next-hop nodes and communication delay measured for the node d_i as,

$$f(d) = max[e^{-(\frac{d}{D})^2},\ \ C]. \tag{5}$$

D defines the basis of communication delay and C decides minimum value of m_i, which characterizes the lower bound of frequency in which ith next-hop node is selected. If the router cannot measure communication delay d_i in some reason, $f(d_i)$ is set C.

Using values of $f(d_i)$ we define dynamics of m_i as m_i linearly decays to $f(d_i)$ with the time constant τ. Finite nonzero value of τ contributes to prevent flapping of packet allocation.

$$\frac{dm_i}{dt} = -\frac{1}{\tau}(m_i - f(d_i)). \tag{6}$$

After updating $\vec{m}$, p_i is also updated as $p_i = m_i/\Sigma_{k=1}^{M} m_k$. We update these values with control period T.

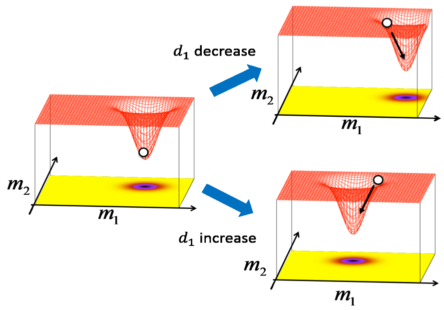

Figure 2: In attractor renewal model, $\vec{m}$ can takes flexible value

Figure 2 schematically shows behavior of the attractor renewal model. Depending on measured communication delay along ith next-hop node, value of m_i changes to converge to $f(d_i)$, which implies that position of the attractor continuously moves.

3. Evaluation of the proposed protocol using network simulations

In this section, we shows validity of the proposal routing protocol with showing that the protocol can properly rearrange packet allocation when traffic along a next-hop node suddenly decrease even though the next-hop node was a suboptimal. Note that, original ARAS cannot notice the decrease of traffic along the next-hop node because the route from the next-hop node was suboptimal and does not used before the traffic decrease.

3.1. Simulation settings

We evaluate performance of the proposed protocol using a queuing network. We generate a random network using the Waxman model [8] of the number of nodes $N = 20$ and the number of edges $E = 30$. Capacity of all link is set to 100 Mbps and propagation delay along them is set to 3 msec. Packet size is fixed to 10000 bits, and TTL is set to 15.

We set simulation time as 300 sec, and the control period T as 1 sec. We also measure performance of the original ARAS with parameters that are set as given [5]. Parameters of the proposal model $\tau = 1$, $C = 0.001$, and $D = 5.0$.

3.2. Traffic variation

In this simulation, we set traffic of all pairs of node that connected each other as 334 kbps excepting one of the congested link that has 100 Mbps. At the time of 75 sec, we decrease traffic of the congested link to 334 kbps. Before 75 sec, both routing protocols, original ARAS and the proposed one, may avoid the congested link to send packets to their destination. After 75 sec, however, in order to decrease communication delay and efficiently use network resources, it must be preferable for routing protocols to allocate packets even to the previously congested link in addition to other links because the congestion has been resolved. Moreover if the congested link is included on the shortest path for some sessions, this session should use the link after 75 sec because the link must give the smallest communication delay.

3.3. Results of simulation

Figure 3 shows the average communication delay of a session that includes the congested link on its shortest path. Before 75 sec, achieved average communication delay of the proposed protocol is bit larger than that of the original ARAS because while ARAS uses only the optimal next-hop nodes to send packet, the proposed model also sends a portion of packets even to suboptimal next-hop nodes to measure communication delay along them. Owing to the seemingly wasteful packet allocation, however the original protocol successfully notice the resolution of congestion on the path and rearrange packets to the route that gives the smallest communication delay whereas the original ARAS

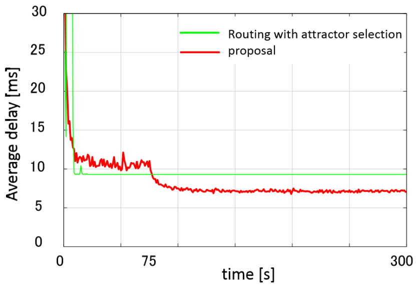

Figure 3: The proposed model can reduce average communication delay after 75 sec while the original ARAS maintains a constant communication delay

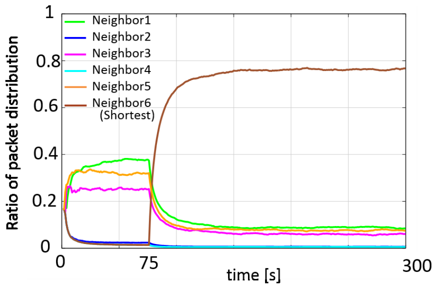

Figure 4: The proposed protocol successfully rearrange packet allocation after 75 sec.

cannot notice appearance of the optimal path that is different from the previously optimal path and cannot decrease the communication delay.

In order to show that above decrease of the communication delay is surely induced by packet allocation, we show time evolution of ratio of packet allocation to next-hop nodes in Figure 4. Before 75 sec, the node sends its packets to next-hop nodes 1, 3, and 5, and rarely sends its packets to the node 6 that gives shortest path because the path contains the congested link. After 75 sec, however, congestion is resolved and communication delay along the shortest path, 6, becomes the smallest value. As shown in the figure, accompanied with the improvement of communication condition along the route, ratio of packet allocation to the next-hop node 6 gradually increases, which results in better performance as shown in Figure 3.

4. Conclusion

In the paper, we have developed a novel adaptive and distributed routing protocol. Unlike the original ARAS, the proposed routing protocol simultaneously multiple paths to send their packet to their destination. Depending on measured communication delays of these paths, the protocol adaptively rearrange allocation ratio of packets. Because of parallel usage of multiple paths, the proposed algorithm can respond traffic change that occurs on previously suboptimal paths, which cannot get noticed by the original ARAS. Using a network simulation with queuing network where traffic on them change in time, we show the proposed protocol surely rearrange traffic allocation and realize routing with smaller communication delay even while the change occurs along paths that are not optimal and rarely used previously.

Acknowledgments

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