nique that is very efficient for routing is AntNet [4], which uses mobile agents that mimic the behavior of ant colonies. It operates by sending forward ants to probe routes and backward ants to update the routing tables at each intermediate node. Traffic is then routed along the paths with certain probabilities. The problem considered here differs from that approach, in that it focuses on the adaptive selection of already determined paths.

## Adaptive Response by Attractor Selection

The biological model of Adaptive Response by Attractor Selection (ARAS) was proposed by Kashiwagi et al. [6] to model how E. coli cells adapt to changes in the availability of a nutrient for which no molecular machinery is available for signal transduction from the environment to the DNA. The appealing feature of this mechanism is that it is highly noise-tolerant and can even be stimulated by noise.

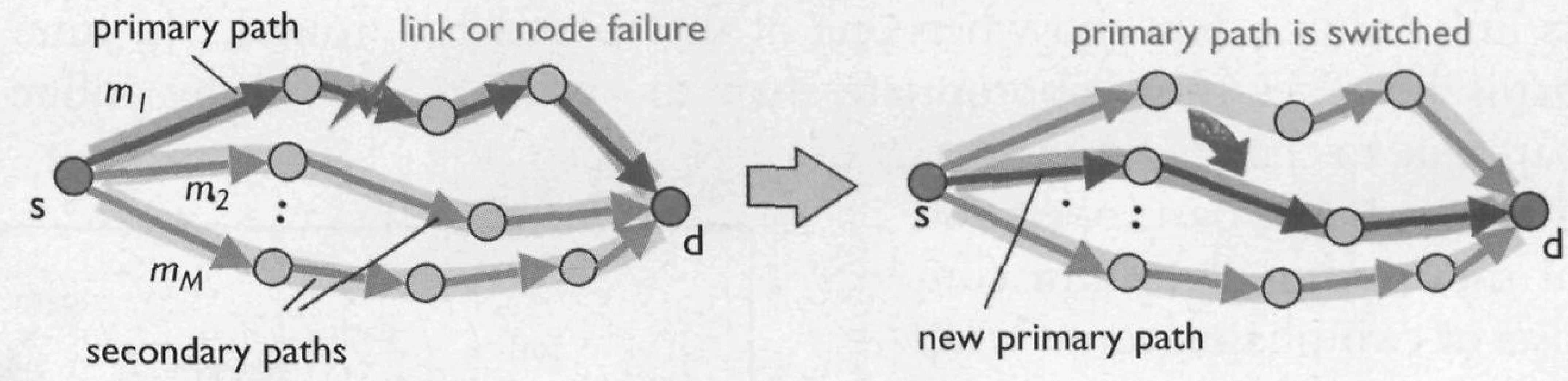


Figure 2. Reaction to failure of primary path.

Basically, ARAS works as follows. Like all dynamic systems, the behavior of the system is characterized by a set of differential equations. Since the underlying method is very mathematical, it is easiest described with a simplified equation as shown in Equation 1.

$$\frac{dm_i}{dt} = f(m_1,\ldots m_M) \times g(\alpha) + \eta_i \qquad i=1,\ldots,M \tag{1}$$

The state of the system is given by the vector over all $m_i$ values and its dynamic behavior is influenced by the two functions $f$ and $g$. When the system evolves over time, it converges to certain equilibrium points that are defined by the product of functions $f$ and $g$ in Equation 1. Additionally, the equilibrium points are constructed in such a way that they are stable *attractors* causing the system state to be automatically drawn to one of these attractors.

Furthermore, each of the $M$ differential equations has a random component $\eta_i$ that corresponds to an inherent noise term found in the original gene expression model. This random noise term causes the system to be constantly in motion; however, once it has converged to an attractor, it remains there as long as the attractor is stable. In our approach, we control the selection of the appropriate attractor by an *activity term* $\alpha$, which indicates how well the current system state corresponds to the considered influencing factors (nutrients) from the environment. The activity directly influences the differential equation system by causing attractors to become instable if the current system state is not suitable for the environmental conditions. In such a case, $g(\alpha)$ would become 0 causing the right-hand side of Equation 1 to be dominated by the random noise term and essentially a random walk is performed. In the course of this random search, the activity value increases again as soon as a better solution is approached and the influence of the random term is reduced (see Figure 1).

To further illustrate how this works, we can make an analogy with a set of electromagnets (attractors) to which the system state (metal ball) is drawn. Each magnet can be activated independently. At any time, only one magnet is active. The dynamic behavior of the activity corresponds to deciding whether the currently activated magnet reflects the current environment conditions. Thus, the abstract formulation of attractor selection can be seen as mapping a continuous input space to a discrete output space, as depicted in Figure 1.

## Multi-Path Routing with ARAS

The technique proposed here is intrinsically applicable to the routing infrastructure of packet-switched networks. However, trying to enhance the IP routing algorithm currently used for the Internet is unrealistic. Instead, a more realistic scenario is to consider overlay routing over an underlying IP network, as for example in the Resilient Overlay Network (RON) [2] architecture. Andersen et al. [2] showed that RON can improve the loss rate and throughput over conventional Border Gateway Protocol (BGP) routing due to its faster reaction to path outages.

Applying the attractor selection scheme to the overlay routing problem can be performed in the following manner. Assume that each node has no exact knowledge of the topology and obtains all information by measurements of its links. For a certain {source, destination} pair with $M$ transmission paths in an overlay network, one path is chosen as the *primary path* depending on the current environment conditions. This is the path with the best metric (smallest latency or highest available bandwidth) and