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An entropy-constrained algorithm for routing of communication networks

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Abstract

This paper introduces an entropy-constrained algorithm for routing of communication networks. The proposed formulation of the routing problem allows multiple nodes to compete for each position in the route, with the associated uncertainty measured by the connection entropy. The problem of determining the best route is subsequently formulated as the constrained minimization of an objective function formed as a linear combination of the routing cost and the corresponding connection entropy. The routing algorithm derived using the method of Lagrange multipliers is implemented by a deterministic annealing optimization process, with the number of accessible system states decreasing gradually with the system temperature. For comparison purposes, routing is also performed by an optimization approach similar with that proposed by Hopfield and Tank and by the routron, which was developed using elements of the Hopfield–Tank approach to optimization but relies on a different treatment of the optimization problem. This experimental study reveals the superiority of the entropy-constrained routing algorithm, which produces consistently the best routes in a small fraction of the time required for convergence by the neural optimization approaches.

Keywords: Communication network; Entropy; Entropy-constrained routing; Route discovery; Route maintenance; Routing algorithm

1. Introduction

A communication network contains a number of nodes, some of which are linked. Routing algorithms aim at discovering the best route between a source node and a destination node. The best route is typically determined based on the topology of the network, i.e., the links existing between the nodes, and some cost associated with every link in the network. In hardwired networks, the cost associated with every link could be the traffic delay between the nodes, which relates to the capacity of the link [9,19]. In wireless networks, the cost associated with every link can be the data rate of the link. In ad hoc mobile networks employing position-based routing protocols, the link costs can also be a function of the distance between the nodes [1–3,12,20].

In addition to their use in route discovery, routing algorithms are also utilized for route maintenance. Route maintenance is a necessary operation for hardwired and wireless communication networks. If routing of hardwired networks relies on the traffic delays between the nodes, the traffic delays between the nodes change continuously with time even if the capacity of the corresponding links remains fixed [9,10,13,15,19]. As an example, the nodes corresponding to links with low traffic delays will be utilized more often than others. This implies that the traffic delays of the links between such nodes will essentially increase. This problem may be dealt with by activating a route maintenance mechanism. In the case of ad hoc mobile networks, the topology of the network and the data rates of the links change continuously since the nodes are free to move relative to each other at variable speeds [1–3,5,11,12,17,20]. In such a case, some of the links might be eliminated while

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other links might be created with time. This reveals the critical role of route maintenance for ad hoc mobile networks.

Route discovery and maintenance are typically performed by well-known algorithms, which include the Djikstra algorithm and the Bellman-Ford successive approximation algorithm [19]. Routing algorithms are required to be flexible and to adapt quickly to changes in network topology and demand patterns. The network must be able to operate under unexpected conditions and must recover quickly from component failures. There requirements imply that routing algorithms must operate in nearly real time to continuously determine the best routes for a network that changes with time. Thus, the computational and storage requirements of routing algorithms become a critical factor in assessing their practical value.

An interesting family of novel approaches to routing of communication networks relied on neural network models. Most of these approaches were influenced by Hopfield and Tank, who suggested that the solution of certain optimization problems can be found by the time evolution of a feedback neural network model realized by a set of differential equations [7,8]. Hopfield and Tank suggested that such an approach can produce satisfactory solutions to NP-complete optimization problems, including the traveling salesman problem [7]. These arguments motivated a series of similar approaches toward the problem of routing communication networks, which can also be formulated as the constrained minimization of a cost function. Rauch et al. [16] used an application-specific neural network for routing communication traffic. This network was merely used as the computational platform for minimizing a cost function that resembles those proposed by Hopfield and Tank. Lee and Chang [14] modified the approach proposed in [16] and they came up with the routron, which was designed for routing communication networks with unreliable components. The routron involves an application-specific neural network similar with that proposed in [16] and a computational procedure developed to produce the best route between a source node and a destination node. Naturally, these approaches to routing of communication networks share the same drawbacks with the Hopfield and Tank's approach toward the solution of the traveling salesman problem [21]. Dixon et al. [4] attempted to overcome the shortcomings of the optimization procedure proposed by Hopfield and Tank by employing mean field annealing to solve the optimization problem involved in routing. Mean field annealing is a methodology developed as an efficient alternative to Monte Carlo simulations and simulated annealing [6]. Mean field annealing was inspired by statistical mechanics and simulates an annealing process by gradually reducing the system temperature.

This paper is organized as follows: Section 2 introduces the connection entropy as a quantitative measure of the uncertainty in the search for the best route between any two nodes, which is used to formulate routing as a constrained minimization problem. This formulation results in an entropy-constrained routing algorithm, which is developed in Section 3. The implementation of the entropy-constrained routing algorithm is discussed in detail in Section 4. Section 5 outlines the Djikstra algorithm and two routing methods based on 'neural' optimization approaches, which are implemented in this study for benchmarking the proposed entropy-constrained routing algorithm. Section 6 presents an evaluation of an entropy-constrained routing algorithm and compares its performance with that of the Djikstra algorithm and neural optimization approaches. Section 7 contains concluding remarks and outlines some interesting problems for future research.

2. Formulation of the routing problem

Let h denote the maximum number of links of possible routes from the source node s to the destination node d. If n is the total number of nodes in the network, then $h \leqslant n-1$. Let b_j^i be a connection coefficient, with the subscript j representing the node number and the superscript i representing the position of the source-to-destination route. The connection coefficients of a legitimate route take on values from the set $\{0,1\}$, with $b_j^i = 1$ indicating that the jth node occupies the ith position of the route and $b_j^i = 0$ otherwise. The connection coefficients in the first position of the route satisfy $b_j^1 = 1$ if $j = s$ and $b_j^1 = 0$ if $j \neq s$. The connection coefficients in the $(h+1)$th position of the route satisfy $b_j^{h+1} = 1$ if $j = d$ and $b_j^{h+1} = 0$ if $j \neq d$. Since the source node s and the destination node d cannot occupy intermediate positions in the route, the connection coefficients of a legitimate route satisfy the conditions

$$\sum_{j \in \mathcal{N}} b_j^i = 1, 2 \leqslant i \leqslant h, \tag{1}$$

where $\mathcal{N} \doteq \{1,2,\ldots,n\} - \{s,d\}$. The connection coefficients $b_j^i \in \{0,\, 1\}$ define a legitimate route if every position in the route is occupied by a single node. Since each node of the network cannot occupy more than one positions in a legitimate route, the connection coefficients $\{b_j^i\}$ define a legitimate route if $b_j^i b_j^r = 0,\ 1 \leqslant j \leqslant n$, for all $r \neq i$. Thus, $\{b_j^i\}$ define a legitimate route if

$$L = \frac{1}{h-1} \sum_{i=2}^{h} \sum_{r \neq i}^{h} \sum_{j=1}^{n} b_j^i b_j^r = 0. \tag{2}$$

If g_{jk} denotes the cost of the link from the jth to the kth node of the network and the connection coefficients $b_j^i \in \{0,\, 1\}$ define a legitimate route, the cost associated with the ith position in the route can be measured as

$$G^i = \sum_{j=1}^{n} \sum_{k=1}^{n} b_j^{i-1} g_{jk} b_k^i + \sum_{j=1}^{n} \sum_{k=1}^{n} b_j^i g_{jk} b_k^{i+1}. \tag{3}$$

According to (3), the cost associated with the ith position in the route is the sum of the link cots between the node that occupies the ith position in the route and the nodes occupying the previous and next positions in the route. The formula in (3) can be verified by assuming that the nodes a,