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ROBUST ROUTING IN NETWORKS OF MOBILE RADIO NODES*

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ABSTRACT

Mobile radio communication networks in the operational theater exhibit volatile network topology with rapid connectivity changes due to node mobility and the harsh conditions in the battlefield environment. Reliable packet transport becomes a chalenging task in view of the constant conectivity changes In this paper we present a systematic approach for reliable packet routing in mobile networks. A class of topology models that is broad enough to capture the topology changes encountered in a mobile network is introduced. The optimal routing policy is specified in terms of the Directed Acyclic shortest path Routing Graph (DARG). Two algorithms for computing the DARG are proposed. One of the two algorithms is iterative and amenable to distributed implementation. The DARG provides shortest path routing in random connectivity networks in analogy to the shortest path tree in fixed connectivity networks.

1 Introduction

Reliable information delivery to mobile radio nodes in the operational theater is a challenging task because of the volatile network topology with rapid connectivity changes due to node mobility and the harsh conditions in the battlefield environment.

The routing algorithms used in wire-line networks presume that the topology of the network remains unchanged for long periods of time. Even the adaptive routing algorithms perform adequately only under quasi-stationary assumptions, where the network changes operational modes but remains in stationary regimes long enough in order for the adaptation to take place. This is not the case in mobile radio networks where the topology changes occur too fast to allow adaptation of these algorithms. Flooding is an algorithm that is robust enough to operate in mobile radio networks since a packet is forwarded to the destination through all possible paths simultaneously. Because of the high degree of packet replication though, flooding creates excessive traffic and the network becomes congested even with moderate loading. While flooding routing may be used for delivery of critical network control or tactical information it cannot be the used for the bulk of information transport needs in the battlefield. In this paper we present a systematic approach for single path routing in mobile networks.

A class of topology models that is broad enough to capture the topology changes encountered in a mobile network will be studied. A network topology state is considered that captures all the essential characteristics that affect the availability or not of the links at each slot t. A packet can be transmitted from the origin node of a link to its destination node in one time slot, if the link is *available* at that slot. A link i is available or unavailable at each slot according to a binary connectivity variable. We assume that the connectivity variables of all links are binary functions of the underlying topology state. At each slot, a packet in some node v may be routed to one of the neighbors of v, if the corresponding link is available, or it may elect to remain in v. Our goal is to find policies for routing a packet to a specified destination node d such that the expected number of time slots to reach the destination is minimized. The problem has been studied extensively for independent

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topology processes. The optimal routing policy has been obtained and characterized in terms of the Directed Acyclic shortest path Routing Graph (DARG) [T96]. That is a subgraph of the original network that contains all its nodes and a subset of the links, is acyclic and has one sink, the destination node d. The shortest path routing policy uses only DARG links for packet transmission. If no outgoing DARG link from node v is available at some slot, then the packet remains in node v. Otherwise it is transmitted through one of the available DARG links that is selected according to some fixed priority ordering imposed on the DARG links. Two algorithms for computing the DARG are proposed. They are the analogs of Dijkstra and Bellman-Ford algorithms in random networks. In addition to computing the DARG, they compute the expected lengths of the shortest paths as well as the implicit priority ordering of the DARG links that is needed in routing. One of the two algorithms is iterative and amenable to distributed implementation. The DARG provides shortest path routing in random connectivity networks in analogy to the shortest path tree in fixed connectivity networks.

2 Optimal Routing with Changing Connectivities

The network is represented by a directed graph $G(I, L)$, where I is the set of nodes and L is the set of the links. The connectivity of the link from i to j is represented by the binary variable $C_{ij}(t)$. If $C_{ij}(t) = 1$, then a packet in node i may be forwarded to node j in one slot. We assume that the sequence of connectivity matrices $C(t), \quad t = 1, 2, \ldots$ is an i.i.d. process. The connectivity probability of link ij is

$$P(C_{ij}(t) = 1) = p_{ij}.$$

Node j is neighbor of node i if $p_{ij} > 0$. We also assume that $p_{ii} = 1$, this means that every node is always connected to itself.

A routing rule for node i is a function $R_i(t)$ whose output is the successor of node i at time t. A routing rule for node i is feasible if

$$R_i(t) = j \ only \ when \ C_{ij}(t) = 1$$

Assume that a packet starts from some arbitrary node of the network and needs to be forwarded to a prespecified destination node. A routing policy is a set of routing rules for all nodes at all times, $(R_i(t) : \quad i = 1, \ldots, N, \quad t = 1, 2, \ldots)$. Our goal is to find the optimal policy under which the expected distance from every node to a specified destination node d is minimized. We consider the class of policies for which at any time instant the successor of a node is selected based on the connectivity matrix $C(t)$ at time t. For these policies the movement of the packet is a Markov chain on the nodes of the graph with the transition probabilities $q_{ij} = Pr(R_i = j)$. For all routing rules of interest this Markov chain has exactly one absorbing state, the destination node, while all other states are transient. The expected delivery time, D_i^R of a packet from node i, is the expected hitting time of d starting from node i of the above Markov chain. Hence the following! equation is satisfied

$$D_i^R = 1 + \Sigma_{j=1}^N P(R_i = j) D_j^R \quad \forall i. \qquad (1)$$

Consider two different routing rules R_1 and R_2. We say that R_1 is dominated by R_2 if and only if,

$$D_i^{R_2} \leq D_i^{R_1} \ \ i = 1, \ldots, N \ \ and \ \ D_l^{R_2} < D_l^{R_1} \ \ for\ some\ l$$

Consider the following condition on a routing rule R:

$$R_i(C) = \arg \min_{j:Cij=1} D_j^R \quad if \ Pr[C(t) = C] > 0 \qquad (\mathcal{A})$$

Proposition 1 *If a routing rule R does not satisfy condition ($\mathcal{A}$), there is another routing rule R' that dominates R.*

Consider the mapping $\underline{M}(.)$ on R_+^N defined as follows:
Given a vector $\underline{X} \in R_+^N$ let $(i_1, \ldots, i_{k_i})$ be the ordered index set of those elements of $\underline{X}$ that are less than X_i. Moreover they are ordered in the set in increasing order of their element i.e.,

$$X_{i_1} \leq X_{i_2} \leq \ldots \leq X_{i_{k_i}} < X_i$$

The ith element of $\underline{M}(\underline{X})$ is

$$\begin{aligned} M_i(\underline{X}) &= 1 + P[C_{ii_1} = 1] \ X_{i_1} + P[C_{ii_1} = 0, C_{ii_2} = 1] \ X_{i_2} \cdot \\ &+ \ P[C_{ii_1} = 0, \ldots, C_{ii_{k_i-1}} = 0, C_{ii_{k_i}} = 1] \ X_{i_{k_i}} \\ &+ \ P[C_{ii_1} = 0, \ldots, C_{ii_{k_i-1}} = 0, C_{ii_{k_i}} = 0] \ X_i \end{aligned}$$

where $C = (C_{ij} : i, j = 1, \ldots, N)$ is a random vector that follows the distribution of the connectivity matrix.

It can be verified that if a routing rule satisfies condition ($\mathcal{A}$) then the associated delivery time vector $\underline{D}^R$ satisfies the equation,

$$\underline{D}^R = \underline{M}(\underline{D}^R) \qquad (3)$$

Also conversely, if a delivery time vector satisfies (3), then the associated routing rule R which has as delivery time vector $\underline{D}^R$ can be readily obtained from $(\mathcal{A})$.

With the help of proposition 1 the following can be shown.

Proposition 2 *The mapping $M(.)$ has a unique fixed point satisfying equation(3). This is the vector of minimum delivery times and the associated routing policy is the optimal policy.*

Let $\underline{X}^n$, $n = 0, 1, 2, \ldots$ be a sequence of vectors derived by the iterative application of $\underline{M}(.)$ to a vector $\underline{X}^0$. The following holds.

Proposition 3 *The sequence $\underline{X}^n$, $n = 0, 1, 2, \ldots$ converges to the optimal delivery time vector from any initial positive vector $\underline{X}^0$.*

Note that the iterative application of $\underline{M}(.)$ accounts only to a simple operation performed by each node i, which involves only the elements X_j^n of the neighbors j of node i. Therefore, proposition 3 suggests a distributed policy for the computation of the minimum delivery time vector and the optimal policy. Using some results from [1] we can prove, that the convergence to the minimum delivery time vector holds even when each node updates its own component of the vector asynchronously from the others. Hence the algorithm is robust.

3 Discussion

The problem of routing in networks with changing topology has been studied in the past. In [2] and [3] algorithms for maintaining loop-free routing paths under changes on the topology were presented. In [4] and [5] results on the optimal routing problems in networks with stochastic variabilities were presented. The objective of the work that is briefly reported in this paper, is to develop a methodology for the design of implementable routing algorithms which adapt to connectivity changes and have near optimal performance. If the topology process is not i.i.d., and it is not expected to be in most cases of practical interest, the optimal routing problem remains open. This is the direction where we focus our ongoing research efforts. We identify three challenges in the correlated case: a) identify correlated topology process which are realistic models of practical topological change scenarios; b) find optimal routing policies when there underlying topology process is observable; c) identify suboptimal routing policies when the topology process is only partially observable. Progress in these directions will lead to efficient, practically useful routing algorithms.

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