A Stochastic Multihop Network Model

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Abstract

Multihop networks achieve robustness and area-coverage by relaying of messages through intermediate nodes. Mobile tactical ad hoc-networks use multihop technique to be independent of pre-deployed infrastructure.

This report describes a basic stochastic simulation model of the end-to-end traffic flow through a multihop network. The main idea is to model a route in network as a single link without the need to consider a detailed internal protocol functionality or node behaviour, such as mobility, routing and traffic. Primary uses for this kind of model would be network-of-network simulations and evaluations of applications used in ad hoc networks.

Keywords: Ad hoc network, delay, Markov model, multihop, path length

Sammanfattning

Flerhoppsnät används för att erhålla yttäckning och robusthet genom att reläa meddelanden via mellanliggande noder. Mobila taktiska ad hoc-nät använder flerhoppsteknik för att fungera oberoende av fast infrastruktur.
Denna rapport beskriver en grundläggande stokastisk simuleringsmodell för trafikflödet genom ett ad hoc-nät. Huvudidén är att modellera en flerhoppsväg genom ad hoc-nätet som en enkel länk utan att behöva ta hänsyn till nätprotokollens interna funktionalitet eller nodernas egenskaper, så som mobilitet, routingmetod eller trafiktyp. Det primära användningsområdet för modellen är nät-av-nätsimuleringar och utvärderingar av applikationer för ad hoc-nät.

Nyckelord: ad hoc-nät, fördröjning, markovmodell, flerhopp, ruttlängd

Contents

1 Introduction

This report describes a basic stochastic simulation model of the end-to-end traffic flow through an ad hoc network. The main idea is to model a route in the ad hoc network as a single link without the need to consider detailed internal protocol functionality or node behaviour, such as mobility, routing and traffic. Primary uses for this kind of model would be network-of-network simulations and evaluations of applications used in ad hoc networks. In both these cases, it is often impractical to perform complicated network simulations. In the first case, detailed simulations would be very time consuming, since radio network protocol simulations are expensive in terms of computational requirements. In the second case, many applications need to be evaluated in real time in order to study human behavior. Ideally, the simulation model should be simple compared to a full-scale simulation but still give a good description of how traffic flows are affected by the transport through an ad hoc network.

The development of such a model can also be helpful in a better understanding of the interior functionality of ad hoc networks. Another potential use is in the ad hoc network nodes, to estimate the available network capacity with limited information about the rest of the network. This, however, will not be the focus of this report. Our primary focus is the modelling of the end-to-end delay of transmitted packets along a route. Packet losses can also be included in this model, where lost packets can be seen to have infinite delay.

1.1 Network Assumptions

In general the behavior of a traffic flow through an ad hoc network differ vastly depending on the properties of the network. Therefore, we need to make some specific assumptions about the network protocols in order to keep the simulation model simple. Note also that some network properties can be handled as initial model parameters when we determine the stochastic properties of the traffic flow, e.g. networks size, terrain, mobility and link data rate.

- *Packet errors* We assume that the network use some kind of error-detecting codes, so that bit errors will simply lead to packet loss. There are no undetected errors in received packets.

- *Routing*: Only one route is used between two nodes in each time instant. This route may be the shortest possible, but that is not necessary. For mobility we assume that rerouting will be immediate and without any cost. The cost for such occurrences can easily be added later by assuming additional states in which the network is handling the rerouting.

- *A TDMA-based slot structure*: The Medium access control (MAC) has a large impact on the behavior of the network. However, protocols as CSMA will generate difficult inter dependences between packets that will be difficult to model if we have long and multiple paths. TDMA-based protocols is preferred for traffic with delay guarantees, since they generate less variance of the delays (jitter), and as such will therefore be simpler to model.

- *Traffic Sensitive Protocols*: With the assumption of using TDMA as a protocol we also need to assume traffic sensitivity in order to get reasonable throughput in the network. We assume each links get time slots in direct proportion to the traffic on that link. This assumption will only affect part of the model though, and it should be possible to expand it without significant changes.

- *Spatial Reuse*: This will affect the actual capacity of the network. In general, increased path length will require packets to be retransmitted more times and thereby cost more resources, however spatial reuse should also increase if the network gets larger. This may affect the performance of the network significantly. We will leave more complicated ways of handling this for now and study it more in further work. As a start we can assume that spatial reuse increase the capacity on a route by a constant factor.

2 Variable Path Length

The primary output of the multihop model is the delay of a packet sent on a path in the ad hoc network. Packet losses can be modelled as packets with infinite delay. The model should not reflect any specific end-to-end pair, but rather be a possible outcome if we choose to simulate a network with similar properties as the one we model.

The actual number of links in a path may differ from path to path and may change over time if the network is mobile. The first step in the modelling process is to generate a distribution of the path lengths and the path lifetime in the network. Also, the likelihood of a change of the path length may be dependent on the present path length as well, as a link failure is more likely on a long path with many links than on a short path.

We model this with a Markov state model where each state represents the number of hops that the path presently has. The model also need a state representing that no path is presently existing, see Figure 2.1.

We assume that the length distribution of newly created paths will not be different from older (rerouted) paths. Such differences could for example occur if rerouting mostly occurs because of link failures, which often increase the length of the route.

A multihop connection may either remain in the current state, representing a certain path length, or change to another state due to rerouting. The probability of a changed path length will be dependent on present path length. The probability of a path length change will in general increase with the length of the path length. For example, a one-hop path will only be rerouted if that specific link fails. The path will in such case always be longer unless no new path exists, while a five-hop path may be rerouted because of failures of any of its links fails or because a new shorter route have occurred. In this case the new route may be shorter, longer, or even of equal length.

To determine the path-length probabilities requires simulations of a large number of generated networks. Some analytical reasoning regarding the life span of a link [1] may help in determining the life span of a path before rerouting. No simulated traffic is needed in the simulations though which will simplify the statistical gathering.

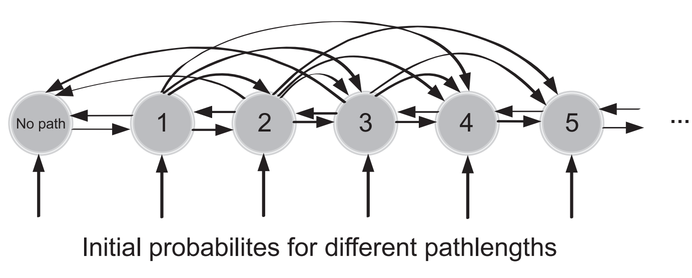

Figure 2.1: The path length model. The numbers in each state represents the present path length. Notice that all possible transitions are not included in the picture.

3 End-to End Delay on a Specific Path

Once a path length is given, the next step is to model the end-to-end delay of the traffic over the path. The end-to-end delay is the sum of all delays for the links in the path. However, the delay of each of the links in the path is not independent, which complicates the modeling. For example, a bursty input traffic load to a link may lead to large delays on that link; however, the output from the link will be less bursty, which means that the delay on next hop will be lower. Seeing traffic as independent on each hop is therefore in general not sufficient.

However, in order to simplify the modeling, without modelling the end-to-end delay entirely from simulation results, we take advantage of the fact that the average end-to-end delay should have less dependence over the different links. By starting with a simplified model of the average delay of a link and use results from queuing theory, we get a fair estimate of the average delay of a path. We can later on estimate end-to-end variations and add those on top of of the average value.

This technique is somewhat limiting though if specific allocations for end-to-end paths are set up, for example to reduce delay for voice applications. In such cases time slots are set up to be consecutive so that very fast passage through the network can be obtained. However, such allocations are very difficult to uphold and no functional method to do this in mobile networks are known at this time.

3.1 Average Delay on a Single Hop

An exact calculation on the average delay on a link is not really possible. It is dependent on the input traffic distribution from other nodes, which in turn is dependent on input traffic to these nodes and so forth. We simplify the problem by assuming that input traffic to the nodes are independent of other nodes.

Under this assumption we use some results from queuing theory. In general both the arrival process as well as the service process is rather complex. Internally arrived traffic only arrive in specific time slots (assuming TDMA), but can arrive from many different neighbors. However, to make the calculations simpler we assume that time slots allocated to a node are equally spread over a frame length, thus giving a deterministic waiting time on the next time slot. We also assume that the interarrival time between packets are exponential so that a Markovian model can be used, an approximation that will simplify the analysis. Formally this give us an M/D/1 queue model for the queuing time.

The average waiting time $E[W]$ for an M/D/1 queue can be written as

$$E[W] = 1/2\frac{\rho F}{1-\rho}, \tag{3.1}$$

where F is the frame length. See [2] for a detailed description. The total delay is this value plus the waiting time until the next time slot and the actual slot length,

$$E[D] = 1 + F + 1/2\frac{\rho F}{1-\rho}. \tag{3.2}$$

The slot length is here set to be equal to one, which means that we measure the total delay in time slots.

This is now the average delay on one link. By adding the values of each link on the path we get the total end-to-end delay. A remaining thing is to determine the unknown in the above formula, i.e. F and ρ. An additional problem is that they can differ from node to node.

If it would be possible to achieve perfect traffic adaptivity, the parameter ρ would have the same value for all nodes. This is normally not possible nor even wanted. Nodes at the edge of a network have easier to get time slots, often without blocking time slots for other nodes. Such slots only helps in decreasing delay and there is little reason to avoid them. Furthermore, different applications have different delay requirements. Keeping ρ equal for all nodes, can have negative consequences for delay sensitive traffic, especially for sessions with low traffic loads (receives time slots seldom due to this) and long paths. Nevertheless, assuming equal ρ could be a starting point for this part of the multihop model.

If the total framelength is equal to T and the number of time slots allocated to node v_i is h_i, this will give us an expression of F for that node equal of T/h_i. In addition, for a fully traffic adaptive network, the number of time slots allocated to a node should be in proportion to the traffic load on that link, i.e. $h_i = X\lambda_i$, where X is a constant for all nodes. Since ρ is equal to $\lambda_i T/h_i$ we can now determine the value of F_{ij} for each node as ρ/λ_i. This means that in order to estimate the average end-to-end delay on a path we need values for the average traffic load level on the network ρ, the distribution of the traffic load λ, the data rate on the links, and the time slot length. These parameters probably need to be obtained from network simulations.

3.2 Delay variations

The performance of many applications, for example VoIP, depends on the variations in the delay of arrived packets. This parameter is called jitter. Estimates of this parameter would be a significant improvement of the multihop model for many scenarios. One potential way of modelling the variations is to study the end-to-end delay of specific fixed paths, and estimate the distribution on the difference from the average delay.

How such a distribution would look like is unclear at this point, though. It will most likely be affected by the path length, and also by the general traffic load of the network. The input traffic also affect the delay variation, but it might be better to separate this from the delay variations created inside the network. Once again we need to resort to simulations to get relevant input parameters for modelling delay variations. Unlike the previous described simulations we here need simulated traffic through the network and not only the routed paths, which will complicate the work.

3.3 Packet loss

Another important behaviour to investigate is packet losses, which is not included in the model so far. We might get infinite delay due to overloading the network, but in reality queue lengths are limited and packets are discarded. Another reason for packet loss is the lossy radio channel. Due to fading and noise, packets may occasionally be lost even in scenarios with a low traffic load.

4 Conclusions and further work

In this report we outlined a basic stochastic network model for the end-to-end traffic flow through a multi-hop network. The model is based on Markov states for the the possible lenght of the paths in the network. We also described how to simplify the modelling of the end-to-end delay on a path.

The next step in the refinement of this model is to determine the transition probabilities between the different states in the path length model. This is achieved by simulating the topology of a large number of mobile networks. From the topolgy changes for theese networks, it should be easy to calculate and collect statistic of the shortest paths between all node pairs in the netwoks.

Bibliography

[1] M. Sköld, Y. Choi, and J. Nilsson. An analysis of mobile radio ad hoc networks using clustered architectures. In *Proc. of VTC03-Spring*, 2003. Reg: FOI-S--1248--SE.

[2] L. Kleinrock. *Queueing Systems Volume I:Theory*. John Wiley & Sons, Inc. New York, 1975.