Disjoint Multipath Routing for Mobile Ad hoc Networks

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In this thesis, we emphasized the need to use multiple node-disjoint paths between a given source and destination. The use of node-disjoint paths not only allows different paths to share the traffic, but also provides fault-tolerance to some extent. However, design of a distributed protocol that relies on partial topology information to identify multiple node-disjoint paths between a given pair of nodes is a challenging task. In this thesis, our main focus is to discuss protocols to discover node-disjoint paths between a given pair of nodes. The contributions of the thesis are as follows.

We considered a model of the network in which nodes are assumed to be distributed randomly though uniformly in a region with specified area. Therein, we obtained analytical bounds to help one to determine as to what transmission range should be assigned to the network devices so that there is no isolated node in the network. This assurance is, of course, with a pre-specified probability. This range also serves as a lower bound on the transmission range required to ensure, with the specified probability, the network to be connected. Similarly, we discussed an analytical expression for the probability that $d_{min} \geq k$, where d_{min} is the minimum node degree. This also serves as an *upper* bound on the probability that there exist k node-disjoint paths between every pair of nodes in the network. This, then, enables one to determine a lower bound on the transmission range for network devices. One should have normally obtained a lower bound on the probability. However, we have shown, using extensive simulations, that the upper bound on the probability is reasonably tight if one were to use the toroidal distance metric. The upper bound on the probability that there exist k node-disjoint paths between every pair of nodes can help in simulations while selecting the transmission range to be assigned to nodes in the network.

The above result falls short of helping one to determine as to what is the number of node-disjoint paths that one should seek from the point of fault-tolerance. This is partly addressed in the next chapter, where we analyzed the time after which all available node-disjoint paths between a given pair of nodes may fail. We discussed an exact expression for the expected value of route failure time where lifetimes of individual paths are independent and identically distributed exponential random variables. When the lifetimes are not independent, we discussed an upper bound on route failure time. The values of route failure time obtained using simulation of exponentially random variables are close to those obtained analytically.

We compared the expected values of route failure time of a multipath system with that of a single path. As expected, the route failure time increases with an increase in the number of node-disjoint paths between a given pair of nodes. However, the increase in route failure time is not significant beyond 2 or 3 paths. Also, a large number of node-disjoint paths between an arbitrary pair of nodes requires the network to be fairly dense. Therefore, we conclude that from the point of enhancement of route failure time, it is sufficient to have 2, 3 or possibly 4 node-disjoint paths between a given source and destination.

In the next chapter, we proposed a protocol called Vertex Disjoint Multipath Routing (VDMR) to discover multiple node-disjoint paths between a given pair of nodes. The protocol is on-demand in the sense that a node initiates a route discovery only when it has packets to send. However, the protocol may not be able to discover all node-disjoint paths that exist in the network between a given pair of nodes. We called this phenomena path diminution. The reason why this happens has to do with the scheme employed in forwarding *route request* (RREQ) packets. If one uses an RREQ forwarding scheme such as Only the First Copy (OFC) then path diminution may be significant.

In an attempt to address path diminution, we proposed three schemes for forwarding RREQ packets. The scemes are: (i) One Copy per Neighbour (OCN), (ii) All Disjoint Copies (ADC), and (iii) Two Disjoint Copies (2DC). We analyzed their effectiveness as well as computational and communication overheads incurred by these schemes. We observed from simulations that the success rate of identifying all node-disjoint paths between a given pair of nodes is significantly improved using the proposed schemes. Further, we compared the performance of VDMR with that of an existing protocol called AODVM. We observed that VDMR with ADC outperforms AODVM in terms of success rate and packet delivery ratio. However, the cost paid is in terms of average end-to-end delays.

There is no guarantee that any of the schemes (including AODVM) discussed in this chapter will always be able to identify all node-disjoint paths that exist between a given pair of nodes. Providing a guarantee for a protocol that discovers multiple node-disjoint paths in *a single route discovery* is very difficult. The difficulty comes from the fact that it is difficult to devise an RREQ forwarding policy that forwards a *limited* number of copies of an RREQ such that all node-disjoint paths can be computed by the destination using traversed paths contained in different copies of the RREQ. If the number of copies of the RREQ that reach the destination is very large, the destination may or may not be able to determine a maximal set of node-disjoint paths in a reasonable amount of time. As a result, if one wishes to provide guarantees, one has to seek an alternative way of determining node-disjoint paths. However, it is possible to provide guarantees if the protocol discovers node-disjoint paths *using multiple route discoveries*. Each route discovery identifies one path between the given pair of nodes, if it exists.

In the next chapter, we discussed a protocol that is guaranteed to discover all node-disjoint paths that exist between a given pair of nodes. This is based on a graph-theoretic framework and an extension of that to a protocol called Multiple Node-Disjoint Paths (MNDP) which discovers node-disjoint paths in an incremental fashion. The number of route discoveries required is exactly equal to the number of node-disjoint paths between the given source and destination. The protocol that we proposed follows a hybrid approach. It is called Multiple Attempt Multipath Routing (MAMR), and is an extension of MNDP. Unlike MNDP, MAMR discovers multiple node-disjoint paths using a scheme such as OFC. This can reduce the number of subsequent route discoveries if the number of paths identified in the first route discovery is more than one.

We compared MAMR with (a) MNDP (b) ADC/OCN. We argued that without incurring a significant additional communication overhead, the incremental protocols (MNDP and MAMR) are guaranteed to discover all node-disjoint paths while no such guarantee is provided by a protocol which tries to discover node-disjoint paths in a *single route discovery*. However, the route discovery time of ADC/OCN is significantly less than those of MNDP and MAMR. We have also argued that number of route discoveries required by MAMR is less than that required by MNDP. A consequence of this is reduction in communication overhead as well as route discovery time.

However, in case of an incremental protocol if the source initiates a new route discovery to identify one more path, the paths identified in the previous route discovery cannot be used until the current route discovery is finished. The reason is that the path discovered in the current route discovery has to be reorganized with the set of paths identified in the previous route discovery. As a result, the route failure time in case of an incremental protocol is less than that of a protocol which identifies multiple node-disjoint paths in a single route discovery. We have shown that the route failure time of MNDP is less than that of MAMR which is in turn less than or equal to that of ADC/OCN.

We conclude that incremental protocols are suitable for low mobility scenarios and for applications where delay is not a stringent requirement. If the number of paths to be identified is fairly small (such as 2 or 3) and the network is dense, a protocol which discovers multiple paths in a single route discovery is preferable. This is because in a dense network, a protocol that uses single route discovery will be able to discover 2 or 3 node-disjoint paths in most of the cases. On the other hand, if the network is sparse and the source wants to determine all node-disjoint paths, an incremental protocol can be used.

For future works, we pointed out many directions in the thesis. Further, one can also explore issues pertaining to the use of node-disjoint paths. For example, one may use multiple node-disjoint paths for providing some form of quality of service. One can also experiment with the use of multiple node-disjoint paths to provide security in case of transferring data from a given source to a destination.

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