SURVIVABLE AD HOC WIRELESS NETWORKS: SOME DESIGN SPECIFICATIONS

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Abstract Survivability analysis and drawing up a specification for a survivable ad hoc network is an important issue that we want to address in this paper. In this paper, we have concentrated on general class of ad hoc networks as well as a special class of ad hoc networks that relies on evaluating link stability and path stability to ascertain the life-span of a path before routing data packets. We have assayed the behavior of the ad hoc network as a whole and analyzed trends in the inter-parameter dependencies, with the objective of addressing to the survivability issues. We have finally drawn out an operating region of survivability for mobile ad hoc wireless networks in terms of user declared specifications.

1. INTRODUCTION

Mobile ad hoc wireless networks are generating novel interests in mobile computing. Lot of research has been done on ad hoc network routing protocols [1,2,3,4] in order to solve the problem of routing data packets. However, there is no complete proposal available to assess the survivability issues in ad hoc network in order to provide a network specification to support effective communication in such a dynamic environment. Survivability analysis in this context can be defined as network design specifications to minimize the impact of system dynamics on the network services . In this paper, we have concentrated on general class of ad hoc networks as well as a special class of ad hoc networks that relies on evaluating link stability and path stability to ascertain the life-span of a path before routing data packets. We have assayed the behavior of the ad hoc network as a whole and analyzed trends in the inter-parameter dependencies, with the objective of addressing to the survivability issues. We have finally drawn out an operating region of survivability for mobile ad hoc wireless networks in terms of user declared specifications. An ad hoc network simulator has been developed and we have derived our survivability constraints from several runs of the simulator.

Traditionally, survivability in network systems has been defined as the capacity of a system to fulfil its mission, in a timely manner, in the presence of failures [5,6]. In the context of ad hoc network, mission fulfillment in a timely manner implies that the network should be able to ensure certain level of service guarantee to its user in the presence of system dynamics. Network service guarantee in the context of ad hoc network is primarily pivotal to two fundamental requirements :

1. establishing a connection between any two nodes in the network whenever desired within a reasonable period of time.
2. Assuring an uninterrupted connection until a finite volume of data has been transferred from a source to a destination.

Survivability issues depend entirely on how well these two demands are met with. Our objective is to design such a set of survivability metrics in terms of the five basic parameters: number of nodes (N), transmission range (R), average mobility (M), average volume of data to be communicated (V) and average number of communication events per unit time (C).

2. SYSTEM DESCRIPTION

The network is modeled as a graph G = (**N**, **L**) where **N** is a finite set of nodes and **L** is a finite set of directed links. Each node $n \in \mathbf{N}$ is having a unique node identifier. Two nodes n and m are connected by two unidirectional links $l_{nm} \in \mathbf{L}$ and $l_{mn} \in \mathbf{L}$ such that n can send message to m via l_{nm} and m can send message to n via l_{mn}. However, in this study, we have assumed $l_{nm} = l_{mn}$ for simplicity.

Affinity a_{nm}, associated with a link l_{nm}, is a prediction about the span of life of the link l_{nm} in a particular context. Thus, the stability of connectivity between n and m depends on a_{nm}. To find out the affinity a_{nm} , node m samples the strength of signals received from node n periodically. Since the signal strength of n as perceived by m is a function $f(R_n, d_{nm})$ where R_n is the transmission range of n, and d_{nm} is the current distance between n and m, we can predict the current distance d_{nm} at time t between n and m. If M is the average velocity of the nodes, the average worst-case affinity a_{nm} at time t is $(R_n\text{-}d_{nm})/M$, assuming that at time t, the node m has started moving outwards with an average velocity M. Given any path p from any node i to another node m as p = (i, j, k, …, l, m), the *stability of path p* will be determined by the lowest-affinity link (since that is the bottleneck for the path) and is defined as: min[$a_{ij,}$ $a_{jk,}$ …, a_{lm}]. In other words, stability of path p between source s and destination d, $\eta^{p}_{sd,}$ is given by $\eta^{p}_{sd} = \min [_{\forall i,j}\ a^{p}_{ij}]$.

However, the notion of stability of a path is dynamic and context-sensitive. As indicated earlier, stability of a path is the span of life of that path from a given instant of time. But stability has to be seen in the context of providing a service. A path between a source and destination would be stable if its span of life is sufficient to complete a required volume of data transfer from source to destination.

3. ROUTE DISCOVERY AND DATA COMMUNICATION MECHANISM IN AD HOC NETWORK

The existing routing protocol can be classified either as proactive or as reactive [3]. In proactive protocols, the routing information within the network is always known beforehand through continuous route updates. The family of distance vector and link state protocols are examples of proactive scheme. Reactive protocols, on the other hand, invoke a route discovery procedure on demand only. The family of classical flooding algorithms belong to this group. It has been pointed out that on-demand reactive protocols are more suitable for highly mobile ad hoc network, since proactive protocols consume large portion of network capacity for continuously updating route information. However, whatever may be the routing scheme, frequent interruption in a selected route would degrade the performance in terms of quality of service. In our earlier works [7,8], we have attempted to minimize route maintenance by selecting stable routes, rather than shortest route. In this scheme, the basic path-searching mechanism is same as in [1] with one differences: the route reply packet from destination to source would collect the most recent value of affinity a_{ij} for all intermediate nodes. When a source initiates a route discovery request, it waits for the route reply until timeout. If it receives a path, it computes its stability $\eta^{p}_{sd.}$ If V_{sd} packets is the volume of data to be send to destination and if B is the bandwidth in packets/msec. for transmitting data, V_{sd} / B is the one-hop delay to transmit the data, ignoring all other delay factors. If H is the number of hops from source to destination, H* V_{sd} / B will be the time taken in msec. to complete the data transfer. If η^{p}_{sd} is sufficient to carry this data, the path is selected. Otherwise, the source checks the next path, if available, for sufficient stability.

4. THE SIMULATION ENVIRONMENT

The proposed system is evaluated on a simulated environment under a variety of conditions. In the simulation, the environment is assumed to be a closed area of 1000 x 1000 meters in which mobile nodes are distributed randomly. We ran simulations for networks with different number of mobile hosts, operating at different transmission ranges. The bandwidth for transmitting data is assumed to be 1000 packets / sec. The packet size is dependent on the actual bandwidth of the system.

In order to study the delay, throughput and other time-related parameters, every simulated action is associated with a simulated clock. The clock period (time-tick) is assumed to be one millisecond (simulated) and one packet per time-tick will be transmitted from a source to its neighbors.

The speed of movement of individual node ranges from 5 meters/sec to 20 meters/sec. Each node starts from a home location, selects a random location as its destination and moves with a uniform, predetermined velocity towards the destination. Once it reaches the destination, it waits there for a pre-specified amount of time, selects randomly another location and moves towards that. However, in the present study, we have assumed zero waiting time to analyze worst-case scenario.

5. IMPACT OF DYNAMIC TOPOLOGY ON CONNECTIVITY AND STABILITY PROPERTIES

5.1 Related Definitions

Average Connectivity Efficiency (E): Connectivity Efficiency has been defined as the ratio of total number of connected node-pairs (in single hop or in multiple hops) and the total number of available node pairs at any instant of time. The efficiency values obtained over several snapshots (taken at intervals of one second from the simulator) of the dynamic environment have been finally averaged to yield the Average Connectivity Efficiency. A network where all the node-pairs are always connected in single or multiple hops have a Average Connectivity Efficiency of 100%.

$$E\,(\%) = \frac{\Sigma^{T}_{i=1}\,(\text{Number of connected node pairs}) * 100}{T * \text{Number of node-pairs}}$$

Average Network Stability (S): From survivability perspectives, the span of time for which two nodes remain connected (given the number of nodes, transmission range and the mobility) need to be analyzed. The stability of the path (i.e. the span of time for which this path would exist) can be determined by the link with weakest affinity in the path. Two nodes in the ad hoc environment may be often connected with several paths. For data communication between two nodes, the best path should always be chosen i.e. the path assuring greater stability. Thus, *Node to node stability* = max [stability of all the paths existing between these two nodes].

The **Average Network Stability** has been defined as the average node to node stability over time.

$$\mathbf{S\ (msec.)} = \frac{\sum_{i=1}^{T} \sum_{\text{all node-pair}} \text{(Node to node stability)}}{T * \text{Number of node-pairs}}$$

Average Number of Neighbors (G): For a random distribution of nodes in a bounded region, broadcast percolation is proportional to the number of neighbors [9], which in turn is a function of node density and transmission range. Average Number of neighbors has been defined as:

$$\mathbf{G} = \frac{\sum_{i=1}^{T} \sum_{\text{all node}} \text{(Number of neighbors of each node)}}{T * \text{Number of nodes}}$$

5.2 Variation of Connectivity Efficiency (E) with N and R

It is quite obvious that if the transmission range R increases, the probability of connectivity also increases. Also, since connectivity is heavily dependent on how close the nodes are with each other, the total number of nodes N in a bounded area also contributes to the connectivity efficiency. Thus, the connectivity efficiency bears a composite relation with the number of nodes as well (Fig. 1). From figure 1, it is quite evident that, to achieve a specific threshold of connectivity efficiency, there is a lower cut off of the transmission range for a given number of nodes and a lower cut off of number of nodes for a given transmission range.

Figure 2 depicts the variation of Average Connectivity Efficiency (E) against Average number of neighbors(G). Over G=6, E is always found to be increasing over 0.8. Over G=8, the network becomes connected and further increase in G would only hike overhead.

Assuming uniform distribution, if the average node density per unit area is λ (= N/A) and A_R is the area of coverage of node i for transmission range R (=ΠR^2), then ($\lambda.A_R - 1$) is the average number of neighbor of node i. It has been shown that the value of $\lambda.A_R$ from six or above have a high probability of leading to a connected network [9]. The optimal value of $\lambda.A_R$ which maximizes throughput has been referred to as “Magic Number” [9,10]. The value of “Magic Number” between six to eight has been proposed in [10] which would optimize the throughput by reducing congestion and collision as well as ensuring connectivity of the network.

5.3 Variation of Network Stability with N, R and M

A high node density in the operating environment essentially indicates that the average distance between two nodes is less in comparison to an environment of low node density. Naturally, if two nodes remain in greater proximity, for a given transmission range and mobility, they would remain in contact for a longer period of time. Consequently the average affinity of links would be higher and thus the average stability of paths. Thus it can be said that the average network stability (S) of a mobile ad hoc wireless network would increase with increase in node density or N (as node density = N / A).

Affinity of a link increases with increase in transmission range and/or decrease in mobility. Average network stability can thus be said to be directly proportional to transmission range and inversely proportional to mobility. This is shown in figure 3.

Average network stability would be dependent on the average affinity between any two arbitrary nodes in the network. Thus, our objective is to derive a relationship between average affinity and the other parameters, namely N, R , M and A in this analysis.

If d_{ij} is the average distance between node i and its neighbor j and G is the average number of neighbors of i, then d_{avg}, the average distance between i and its neighbors is

$d_{avg} = (\sum_{j=1}^{G} d_{ij}) / G$, where $G = (N / A) * \Pi R^2 - 1$.

Let d_{i1} be the average distance between node i and its nearest neighbor, d_{i2} be the average distance between node i and its second neighbor, and, so on.

Assuming uniform distribution of nodes over the area A and i as center of the circle with radius d_{ij},

$\Pi d_{i1}^2 * N/A = 1$; $\Pi d_{i2}^2 * N/A = 2$;   …; $\Pi d_{iG}^2 * N/A = G$.

Hence, $(\sum_{j=1}^{G} d_{ij}) = (\sqrt{(A / \Pi N)}) * (1 + \sqrt{2} + \sqrt{3} + \ldots + \sqrt{G})$

So, $d_{avg} = (\sqrt{(A / \Pi N)}) * (1 + \sqrt{2} + \sqrt{3} + \ldots + \sqrt{G}) / G$

Average Affinity, $\eta_{avg} = (R - d_{avg}) / M$.

As an example, for N=30, G = 6, M =10 m/sec and A = 1000 x 1000 sq.meter, we can calculate R as $R = \sqrt{(A*G / \Pi N)} = 252$ meter and $d_{avg} = 185.5$ and $\eta_{avg} = (252 - 185.5)/10 = 6.6$ sec.

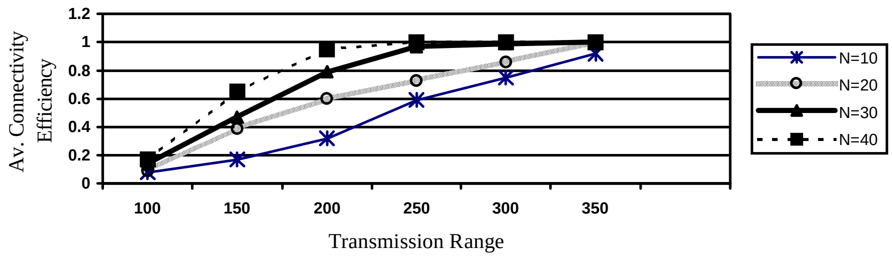

Figure 1. Average Connectivity Efficiency(E) vs. Transmission Range(R) for different Number of Nodes

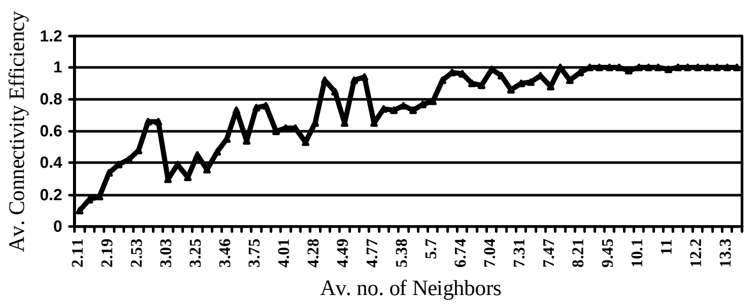

Figure 2. Average Connectivity Efficiency (E) vs. Average Number of Neighbors (G)

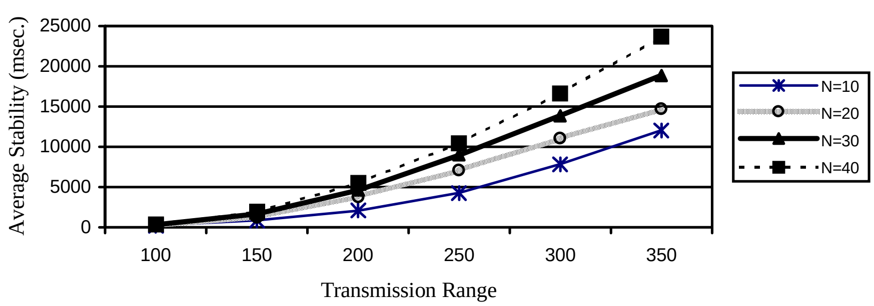

Fig 3. Average Network Stability vs. Transmission Range at Mobility M=10 m/sec

6. IMPACT OF ROUTE DISCOVERY AND DATA COMMUNICATION ON SURVIVABILITY

The above analysis does not take into account the congestion and collision factors that would happen during data communication. We will show that even if a network is well-connected, it may not guarantee successful data communication.

6.1 Related Definitions

Route Discovery Efficiency is defined as the ratio of the average number of route replies obtained per minute and the average number of route request generated per minute. The success of route request i.e. getting a route reply back within a reasonable period of time (500 msec in our case) would depend on the degree of collision and congestion of the network. This is not only dependent on E but also on the average volume of data communicated from a source to its destination (V) and frequency of communication events per minute (C). If C and / or V increases, the probability of collision and congestion would increase, which in turn will affect the Roure Discovery Efficiency.

Service Efficiency is defined as the ratio of the average number of communication events successful within a reasonable period of time per minute and the average number of route request generated per minute. Service_Efficiency depends on four factors : 1) Route request has been generated but route reply has not come back within a reasonable period of time, 2) Route replies have been obtained but the paths are rejected because they are not stable enough to carry out the required volume of data transfer, 3) A path is selected and data communication has started but the path could not be retained throughout the entire period of data communication, and, 4) the network delay is too high to complete the data transfer within a reasonable period of time. It has been shown in [7] that the use of stability based routing reduces the probability of (3) drastically. However, the prediction of stability would be affected, if the network is heavily congested which will in turn affects the Service Efficiency.

6.2 Variation of Number of Packets in Output Queues

The total number of control packets and data packets in the output queues of all the nodes in the network at any instant of time is a measure of the load situation of the network. The growth and decay of output packets in the network depends on E, C and V. A high E implies that that average number of neighbors of each node is high and therefore the growth of control packets in the network is exponential until they decay after they travel the max-hop number of hops. A high value of C implies the starting of a second route discovery before the decay of the first one, resulting in further queue accumulation. A high V implies high queue accumulation during the data transfer. From survivability point of view, if the number of communication per minute (C) and / or the data volume (V) crosses a certain threshold, then the network will not find time to absorb the packets accumulated in the output queues. In other words, the value of C and V should be such that Q gets the time to decay below certain threshold value.

Let us assume that a source S initiates a route discovery at t=0. Let us also assume that G is the average number of neighbors of S, the bandwidth is B packets/sec. and max_hop=4. At t=1/B sec., all the nodes in G will receive the first-hop route request. If all the nodes in G are neighbors, then each node in G will broadcast the route request packet sequentially to each of its neighbors. However, this is the worst-case assumption, because there is a chance that some of the nodes in G are not neighbors of each other and they may broadcast route request packets simultaneously.

Let G_i be the average number of neighbors of i^{th} node in G to receive the second-hop route request from S. So, considering worst-case assumption and no loss of packets due to collision, at t (sec)=(1+G)/B, $\Sigma^{G}_{i=1}G_i$ packets would be delivered to the neighbors of all the nodes in G.

Let G_{ij} be the average number of neighbors of j^{th} node in G_i to receive the third-hop route request from S. Once again, assuming sequential broadcast and no loss of packets due to collision, at t(sec)= $(1+ G+ \Sigma^{G}_{i=1}G_i)/B$, $\Sigma^{G}_{i=1} \Sigma^{Gi}_{j=1} G_{ij}$ packets would be delivered to the neighbors of all the neighbors of all the nodes in G.

Proceeding in this fashion, at t(sec) $=(1+ G+ \Sigma^{G}_{i=i}G_i + \Sigma^{G}_{i=1} \Sigma^{Gi}_{j=1} G_{ij})/B$, fourth-hop route request packets would be delivered to the neighbors of fourth-level neighbors and they are consumed. So, ignoring packet losses due to collision and considering sequential broadcast at each level, the time required to see the complete decay of a route-request packet generated at S and propagated through four-hop paths in the network is:

T_C (sec)= $(1+ G+ \Sigma^{G}_{i=i}G_i + \Sigma^{G}_{i=1} \Sigma^{Gi}_{j=1} G_{ij})/B$

If G_{avg} is the overall average number of neighbors of each node, T_C can be approximated as $T_{Cavg} = (1+G_{avg}+ G^2_{avg} +G^3_{avg})$ /B sec.

Let us now focus on data communication. If V is the data volume in packets, bandwidth is B packets/sec. and H is the number of hops from source to destination, then at T_D (sec) =V*H /B, all the data packets would be delivered, ignoring RTS / CTS exchange time. Once again, T_D can be approximated as $T_{Davg} = V*H_{avg}/B$, where H_{avg} is the average number of hops from any source to destination at a given N and R. So. $T = T_{Cavg} + T_{Davg}$ would be the average time required to consume all packets in the output queue.

6.3 Variation of Route Discovery Efficiency

The congestion due to control packets at high transmission range would affect the Route Discovery Efficiency as shown in Figure 4. For a fixed number of N, there is an optimum value of R, R^{Nopt}, which will maximize the route discovery efficiency. Increasing R beyond that point will increase the Average Network Connectivity, but degrades the Route Discovery Efficiency due to congestion and collision of control packets. However, R^{Nopt} alone can not maximize route discovery efficiency. We need to consider two more factors : average volume of data to be communicated from a source to its destination (V) and average number of communication events per minute (C). As shown in the last section, the system should be capable of absorbing the control and data packets before a new communication event starts. The value of C and V should be such that the output packets get the time to decay below a certain threshold value. If not, the Route Request packet will either be lost due to collision or the corresponding Route Reply packet will not come back to source within Route-Request-Time-Out.

6.4 Variation of Service_Efficiency

For a given number of node and corresponding R^{Nopt} , the variation of Service_Efficiency against M for different V and C=10/min. is shown in figure 5. It is evident that getting a high Service Efficiency at M=20 is difficult to obtained in this set up, particularly with high data volume. The reason is that we are not getting sufficient stable paths to complete the data transfer at that mobility. Moreover, the effect of network congestion is substantial for high data volume. On the other hand, for lower volume of data and/or low mobility, it is always possible to get a Service_Efficiency > 80%.

From this analysis, we are in a position to answer questions like :What should be the transmission range and the maximum mobility for an ad hoc network with 30 users, if the user require a Service_Efficiency of 80% and 1000-Kb average data volume for transfer at the average rate of 10 communication event per minute? The kind of answers we are trying to provide is that, for 30 users with a transmission range of 300 meters, it is possible to achieve the required Service_Efficiency with V<=1000, if the average mobility is less than 10.

7. SURVIVABILITY METRICS AND SPECIFICATIONS

The aim of our entire analysis is to model the survivability region of operation for a mobile ad hoc wireless network. In order to derive specifications for a survivable ad-hoc network, the following five rules are applicable:

Rule 1. Given area of operation A, compute N or R such that G_{avg} should be between 6 to 8 where $G_{avg} = (\Pi NR^2 / A - 1)$

Rule 2. Given mobility M, compute average network stability $S = (R - d_{avg})/M$ where $d_{avg} = (\sqrt{} (A / \Pi N))* (1 + \sqrt{2} + \sqrt{3} + \ldots + \sqrt{G_{avg}}) / G_{avg}$

Rule 3. Given average bandwidth as B packets / sec., compute maximum volume of data that can be transferred at a time from a source to a destination as $V_{max} = B*S/H_{avg}$, where H_{avg} is the average hop-count from source to destination and S is in seconds.

Rule 4. Compute $T = T_{Cavg} + T_{Davg}$ where $T_{Cavg} = (1+G_{avg}+ G^2_{avg} +G^3_{avg})/B$ sec. and $T_{Davg} = (V_{avg}*H_{avg}) / B$ sec. Where V_{avg} is the average volume of data that would be transferred from source to destination.

Rule 5. Compute maximum number of communication events per minute as $C_{max} = 60/T$

8. DISCUSSION

It has been observed that optimal transmission range, R^{Nopt}, for a fixed number of nodes is playing a crucial role in survivability. However, R^{Nopt} alone can not minimize delay or maximize route discovery efficiency. We need to consider two more factors : average volume of data to be communicated (V) and average number of communication events per minute (C). Depending on R^{Nopt} and the average mobility M, we can specify average network stability which will in turn determine V. If we increase M or V beyond that, the Service Efficiency will suffer.

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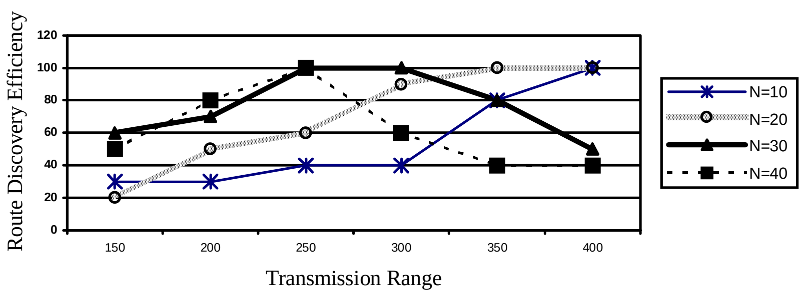

Figure 4. Route Discovery Efficiency vs. Transmission Range for V=100 and C= 10 / minute.

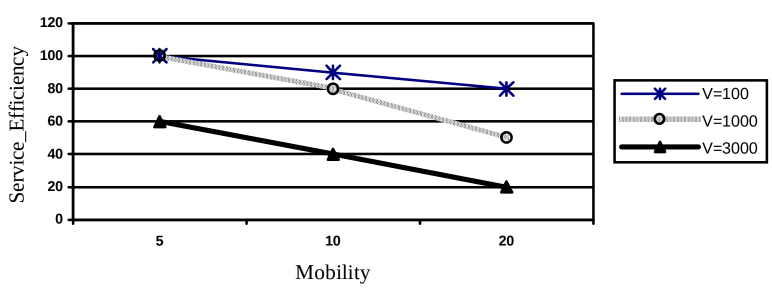

Figure 5. Service_Efficiency vs. Mobility with No. of Comm.=10/min and N=30 & R=300