Connection Resilience to Nodes Failures in Ad Hoc Networks

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Abstract— **The failure of nodes in an ad hoc network not only alters the network topology but also introduces severe changes in the ad hoc network performances. Based on the ad hoc network connection availability model, in this paper we propose measures of ad hoc network fault tolerance expressed as connection resilience to nodes failures and relative connection resilience to nodes failures. Also qualitative evaluation of these measures is presented and then used to evaluate the effects of real measurable ad hoc networks parameters that concern the resilience to nodes failures like number of participants in the ad hoc network, source destination distance, mobility model, average node speed, transmission range, routing protocol and size of the area wherein the nodes are scattered.**

I. INTRODUCTION

Mobile Ad-hoc NETworks (MANET) have become more and more popular, during the last ten years [1]. Although one of the original motivations for ad hoc networks found in military applications still dominate the research needs in ad hoc networking, the recent rapid advent of mobile telephony and plethora of personal digital assistants has brought to the fore a number of potential commercial applications of ad hoc networks.

An ad hoc network is a collection of wireless mobile nodes dynamically forming a temporary network without the use of any existing network infrastructure or centralized administration. The nodes are expected to act cooperatively to establish the network "on-the-fly" and route data packets possibly over multiple hops. Node mobility and limited power introduce rapid changes in network topology, connectivity and links characteristics.

Because of the emphasized collaboration aspect of ad hoc networks, the nodes failures have great impact on their global performances, connectivity and availability. Hence, in this paper we inspect this influence on the ad hoc network characteristics.

Resilience is one the fault tolerant measures that describes the network flexibility in the presence of node failures. This measure has several different definitions depending on the network type and nature of performance criteria. Network resilience, as defined by Najjar and Gaudilot [2], is the maximum number of node failures that can be sustained while the network remains connected with a given probability. The term "network resilience" has also been used by Colbourn [3] as the expected number of node pairs that can communicate when faulty nodes exist. Newman [4] defined the network resilience as robustness of networks to removal of nodes. In order to express the impact of node failure to network resilience he uses the fraction of high-degree vertices which removal will destroy the giant component as a quantitative measure. Albert et al. [5] addressed the error tolerance of the networks, by studying the changes in diameter when a small fraction f of the nodes is removed. Considering the multipath routing in wireless sensor networks, the authors in [6] defined resilience to isolated failure as the probability of at least one alternate path being available within the interval T, given that at least one node on the primary path has failed.

Therefore, the term resilience implies to network fault tolerance depending on node failures. All of the above-mentioned definitions assume existence of fixed network infrastructure that does not exist in ad hoc networks. Hence, while defining resilience for ad hoc network, the number of participant nodes needs to be taken into account.

In order to observe this property, we need to examine measures that will allow us to inspect the network performances when node failures occur. For wireless (and wireline) networks, the network's ability to avoid or cope with failure is measured in three ways: reliability, availability and survivability [7]. Each of the mentioned measures can be reviewed from different aspects like two-terminal, k-terminal and all-terminal. The two terminal measure measures the ability of the network to satisfy the communications needs of a specific pair of user terminals (connection), thus being a user view of the network fault tolerance. Hence, in this paper we model the connection resilience to node failure for ad hoc networks using connection availability as a reference measure.

II. AD-HOC NETWORK MODEL DESCRIPTION

Since real world radio networks are influenced by many factors like irregular terrain, asymmetry radio transmission, and radio interference, in order to give a simplified, but reasonable model we make some assumptions. To simplify our study, we assume that the terrain is perfectly flat while all the mobile nodes (MN) have the same fixed transmission power and are equipped with omni directional antenna, thus having equal transmission range r. This assumption turns the node radio coverage shape into a perfect circle with radius r.

In our model we use N+2 nodes placed in area A. Two of the nodes are the source and the destination nodes for the end-to-end connection, and the rest, N nodes, can be part of the connection path between the source and the destination, therefore playing the part of routers in this end-to-end connection. In order to establish a communication between the two mobile nodes MN_s and

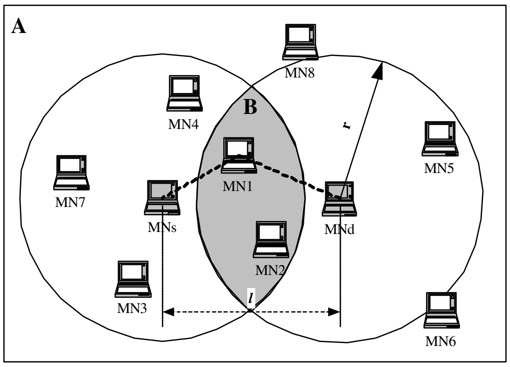

Figure 1. Ad hoc network model

MN_d (l is the distance between MN_s and MN_d $r<l<2r$), the communication path has to go through one of the nodes (MN_1, MN_2) that are currently located in the intersection area B between MN_s and MN_d (see Figure 1.). While moving around in A, a node can enter the B area and, after a certain period of time, leave B and enter area C defined as A-B. This process is continuously repeated.

Similar to [8] and [9] we use a two-hop scenario because of the complexity of the development of an analytical model for multihop scenario.

III. CONNECTION RESILIENCE MODEL TO NODE FAILURE

In order to create a connection resilience model to node failure, we start with connection availability model that is proposed in [10] and enhanced in [11]. Availability is a network's ability to perform its functions at any given instant under certain conditions, while steady state availability is a function of how often something fails and how long it takes to recover from a failure [2]. The connection availability is modeled as a parallel system of N components with N repair facilities that depends on the leaving rate λ (failure rate), returning rate μ (repair rate), number of participants in network N, average switching delay $1/\delta$ and connection reestablishment delay $1/\delta_r$ (see Fig. 2). For the purposes of simplifying the continuous time Markov chain (CTMC) model the following assumptions are made: all entering and leaving events in the intersection region are mutually independent, exponential distribution is assumed for time of occurrence of each enter and leave event, and the average switching delay is small compared to the average time a routing node spends in the intersection region. The states of the CTMC model are labeled with tuple (i,j) where $i\in\{0,1,2,\ldots,N\}$ represents the number of nodes currently in the intersection region (the total amount of nodes is $N+2$), and $j\in\{0,1,2,3\}$ represents the state of the connection ($j=0$ no fault, connection is up, $j=1$ route discovery state, $j=2$ waiting for route reestablishment, $j=3$ no routing nodes available). The failure rate λ is the rate of leaving the intersection region B, while the repair rate μ, is the rate of the nodes returning into the B region.

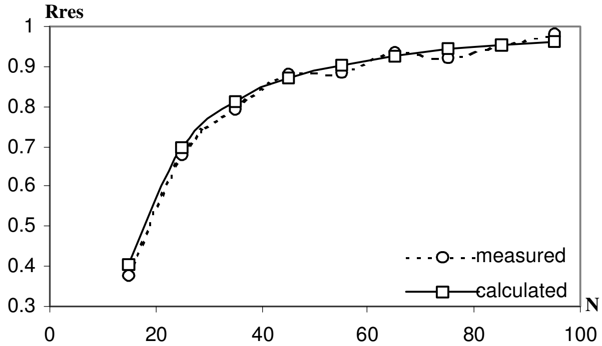

Figure 3. Simulated and calculated relative connection resilience to nodes failures depending on number of nodes

The steady state connection availability (SSCA) is

$$A_s(N)=\sum_{k=1}^{N}\frac{N!}{k!(N-k)!}\left(\frac{\mu}{\lambda}\right)^{N}\pi_{0,3} \qquad (1)$$

$$\pi_{0,3}=\frac{1}{\left(1+\frac{\lambda}{\delta}\right)\left(1+\frac{\mu}{\lambda}\right)^{N}-\frac{\lambda}{\delta}\left(1+N\frac{\mu}{\lambda}\right)+N\frac{\mu}{\delta_r}} \qquad (2)$$

According to [12], all communication systems faults are classified into two major groups physical and software faults. The physical faults that affect the end-to-end connection in communication systems are: node, power and link faults. In our paper, the term node failure incorporates node and power faults after which the node is no longer a participant in the ad hoc network.

In order to express the ad hoc network flexibility, we define two types of connection resilience to nodes failures: connection resilience to nodes failures (CRNF) and relative connection resilience to nodes failures (RCRNF).

The connection resilience to nodes failures in ad hoc network that contains N nodes is defined as the greatest number of nodes k_{max} that can be removed from the ad hoc network while the connection availability remains above a predefined critical level, A_c.

$$Res(N,A_c)=k_{max},\ \text{where}\ A_s(N-k_{max})>A_c \qquad (3)$$

where $A_s(N)$ is the connection steady state availability given with (1). The values of connection resilience close to 0 represents lack of resilience, and the bigger values show that the network still offers the critical availability level although there are failed nodes.

The relative connection resilience to k nodes failures in an ad hoc network that contains N nodes is:

$$Rres(N,k)=1-\frac{A_s(N)-A_s(N-k)}{A_s(N)} \qquad (4)$$

where $A_s(N)$ is the connection steady state availability given with (1). It has values between 0 and 1. The values close to 1 represent great flexibility of the ad hoc network to node failures, while the values close to 0 represent network rigidity.

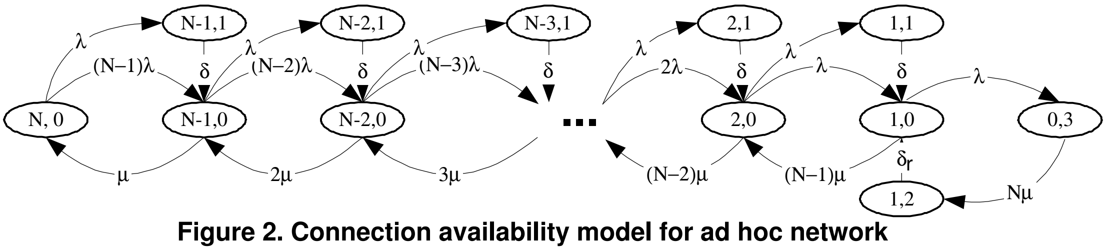

Figure 2. Connection availability model for ad hoc network

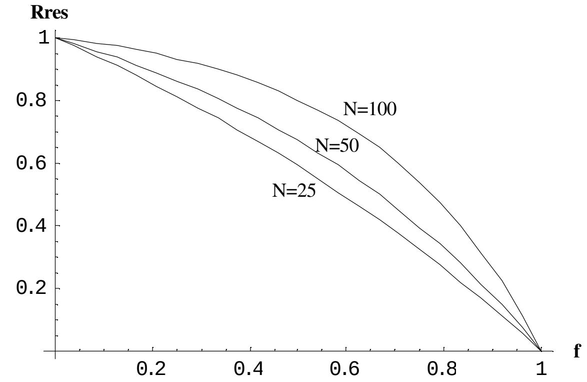

Figure 4. Relative connection resilience to nodes failures depending on the fraction of failed nodes

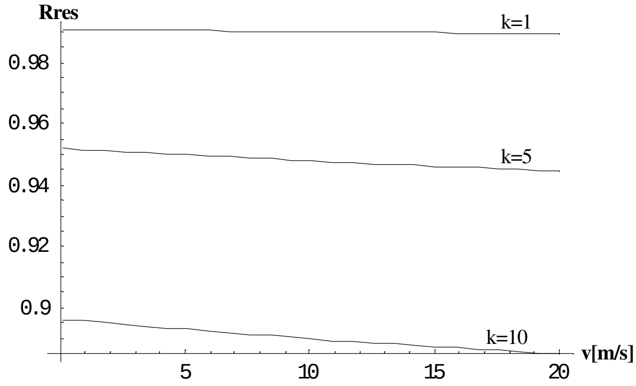

Figure 5. Relative connection resilience to nodes failures depending on the node speed

In order to confirm the connection resilience model we simulated a number of two hop ad hoc scenarios using the NS2 network simulator [15]. We analyzed the RCRNF on network with different number of nodes. The simulation scenario was made in several series using different source-destination node placement and Random Walk mobility model [13]. As shown on Fig. 3, the results have corresponded to the anticipated connection resilience model.

IV. MOBILITY PARAMETERS

Connection resilience to nodes failures in ad hoc networks depends on many factors: routing protocol, number of participants in network, nodes velocity, mobility model, transmission range and size of the area wherein the participants in the ad hoc network are scattered. One of the main goals of this paper is to obtain the influence of these factors over the connection resilience on nodes failure.

Both, the transmission range and the distance between the nodes, affect the size of the intersection area B [10]:

$$B = r^2\left(2ArcCos(\frac{a}{2}) - a\sqrt{1-\frac{a^2}{4}}\right) \qquad (5)$$

where r is transmission radius, a is relative distance between the nodes $a=l/r$ and l is distance between the nodes ($l \in [r,2r]$, $a \in [1,2]$).

In order to obtain the leaving rate, we must obtain the average time $\bar{t}_B$ that a mobile node spends in the intersection region between the two communicating nodes MN_s and MN_d. Due to the shape of the intersection region, this is called the "eye of coverage" (see Fig 1.). The MN movement is according a given mobility model. There are several mobility models that are used in performance evaluations for ad hoc networks. The most commonly used models are Random Walk and Random Waypoint [13]. In both mobility models linear motion and uniformly distributed speed between [minspeed, maxspeed] is used. If the intersection region is reasonably small relative to the whole area, we can presume that no changes of direction happen in the intersection region, namely the node passes the intersection region in a straight line with a constant speed. At these conditions the time needed to pass the intersection region is given by $t=d/v$, where d is length of path that MN passes through the intersection region (eye path) and v is MN speed uniformly distributed random variable. The eye path d is a random variable and its value depends only on the entry point into intersection region and the entry angle. The average time that a node passes into the intersection region [11] is given by:

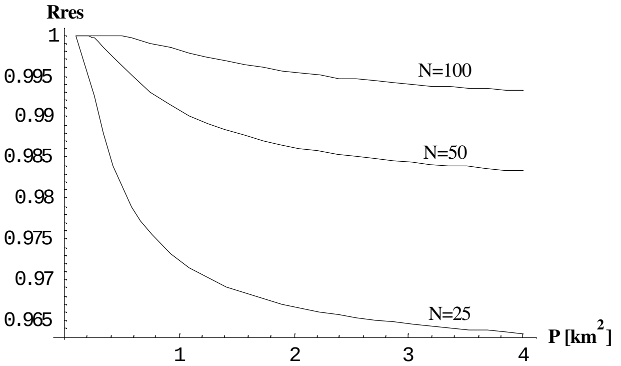

Figure 6 Relative connection resilience to nodes failures depending on the area wherein the nodes are scattered, k=1.

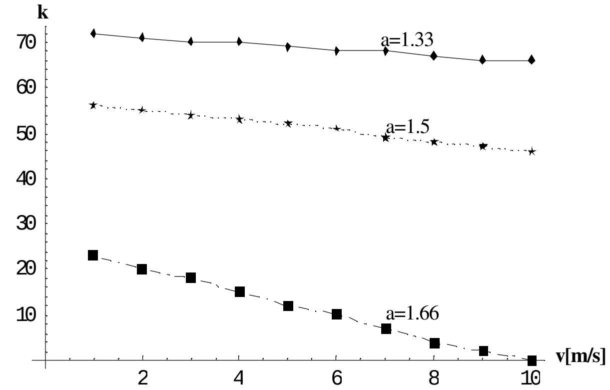

Figure 7. Connection resilience to node failures depending on the node speed for several relative source-destination distance

$$\bar{t}_B = \frac{\ln(\bar{v}+\sigma\sqrt{3}) - \ln(\bar{v}-\sigma\sqrt{3})}{2\sigma\sqrt{3}}\bar{d} \qquad (6)$$

where $\bar{d}$ is the average length of path that a MN passes through the intersection region, $\bar{v}$ is the average speed of the node and σ is the standard deviation. The average time that a MN passes outside the intersection region B [11] is

$$\bar{t}_C = \frac{p_C}{p_B}\bar{t}_B \qquad (7)$$

The leaving rate for intersection area B is $\lambda = 1/t_B$ and the leaving rate for area C (returning rate for intersection area B) is $\mu = 1/t_c$.

V. CONNECTION RESILIENCE TO NODES FAILURES ANALYSIS

The analysis of connection resilience to nodes failures that depends on the parameters previously defined is made for an example rescue mission application of ad hoc networks. The mobile nodes are located in area A=1,000,000m^2, while the use of IEEE 802.11 protocol results in transmission range r=250m. In order to be sure, with a probability of at least p, that no node in a ad hoc network with N>>1 nodes and homogeneous node density $\rho = N/A$ nodes per unit area is isolated, the node transmission radius r according [14] must be set to

$$r \geq \sqrt{\frac{-\ln(1-p^{1/N})}{\pi} \cdot \frac{A}{N}} \qquad (8)$$

The no-isolated-node probability is a measure of the ad hoc network connectivity and here it is used to calculate the number of nodes needed to achieve connected ad hoc network for a given area A and transmission range r. Solving equation (8) for A=10^{6}m^2 and r=250m we get N=42 nodes (because of the border effects we use N=50). The value of the relative distance between MNs and MNd nodes is a=1.5m (average distance) in all cases. The standard deviation for the node speed σ is 0.01, hence the node speed is nearly constant.

In order to investigate the impact of the previously mentioned parameters on the connection resilience to nodes failures in ad hoc networks we make several observations. RCRNF for different number of nodes in the ad hoc network depending on the fraction of failed nodes is shown on Fig. 4. It can be seen that RCRNF decreases with the increasing fraction of failed nodes. The bigger number of nodes results into increased connection resilience. On Fig. 5, the RCRNF depending on the average node speed for several numbers of failed nodes is shown. It is obvious that when the speed increases the relative connection resilience reduces because, when considering average speeds < 50m/s, the average node speed impact on the connection availability is greater when the number of nodes is bigger. On Fig. 6, the RCRNF for one node failure depending on the size of the area wherein the nodes are scattered is shown for several numbers of participants in the ad hoc network. With the decreasing number of nodes the relative connection resilience to nodes failures decreases more rapidly when the size of the area is growing. It is interesting to stress that for area sizes up to 1km^2 and relatively large number of nodes, the ad hoc network is almost completely flexible to node failure, that is, its relative resilience equals 1.

The CRNF for different relative source-destination distances depending on the average node speeds is shown on Fig. 7. CRNF decreases with the increasing node speed since the connection availability critical level becomes more difficult to maintain. When the distance between the source and destination node increases the CRNF decreases more rapidly because this parameter has a big influence over the connection availability.

VI. CONCLUSION

Because of the need for performance analysis for ad hoc network when node failures occur, in this paper we introduce two new fault tolerance measures: connection resilience to nodes failures and relative connection resilience to nodes failures. The first measure is defined as the greatest number of nodes that can be removed from the ad hoc network while the connection availability remains above a predefined critical level. The relative connection resilience to nodes failures in an ad hoc network that contains N nodes is defined as the relative connection availability difference. Both of the measures represent the ad hoc network flexibility to nodes failures from the user point of view. Starting from the connection availability model we developed analytical expressions for the newly introduced measures.

Using the proposed measures we also made several analyses of the impact of real measurable parameters on the ad hoc network flexibility in faulty environment. The analyses have shown that the increasing average node speed reduces the node failure resilience, similar to the increasing size of the area wherein the nodes are scattered.

The main purposes for the newly introduced ad hoc network resilience measures are creation of fault tolerant ad hoc networks that will offer connections with a guaranteed minimal level of availability to their users.

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