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Survivability Modeling and Analysis of Mobile Ad Hoc Network with Correlated Node Behavior

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Abstract

This paper present a new survivability model based on correlated node behavior to study the global survivability of mobile ad hoc networks. The model uses k -correlated survivability model for correlated node behavior of mobile ad hoc networks which is an extended version of k -connectivity of individual node model. The k -correlated survivability model takes correlated degree ω to measure node correlation as a new function of survivability. The study evaluates the impact of correlated node behavior particularly selfish, malicious and fails nodes toward network resilience and survivability. The results show that correlated node behaviors have more adverse effects on the survivability.

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1. Introduction

Survivability of mobile ad hoc networks is a major importance to its successful operation and is becoming increasingly important as networks grow in size. While cost is a prime consideration, ensuring adequate network survivability is also an important part of the networks design. Survivability analysis of mobile ad hoc network has been studies for many years, and numerous algorithms and evaluation techniques have been proposed [1][2][3]. However, almost all of them make the assumption that node behaviors are mutually independent. For most real world scenarios, these assumptions do not adequately reflect the nature of real world network environments. This independence assumption is carefully examined in [4], and is shown to be inaccurate.

Correlated behaviors in mobile ad hoc networks commonly arise from other nodes behavior as well. For example, if a node has more and more neighbors failed, it may need to load more traffic originally forwarded by those failed neighbors, and thus might become failed faster due to excessive energy consumption. Similarly, it is also possible that the more malicious neighbors a node has, the more likely the node will be compromised by its malicious neighbors. The researches discuss on correlated behavior deal with systems or network reliability and availability, nevertheless none of them is considering the unique feature of ad hoc networks and the potential impact of all kinds of node behaviors. We know that from literature [5], correlated node behavior will result in unstable network which impact survivability,

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reliability and availability. It is also proven that the impact of correlated misbehave node is quite challenging due to multiple attacks and failures caused by node mobility, energy depletion and Denial of Services (DoS) attacks [6].

2. Related Works

There are several papers discussing correlated node effects in various contexts. In [7] a framework is presented to model correlated effects caused by disasters on networks; nonetheless, the model is limited to bipartite networks and vertical regional disasters. Another work discusses availability of storage systems in the presence of independent and correlated failures [8]; where correlated failures are modeled based on datasets using conditional probabilities and the beta-binomial model. A tunable failure correlation model is reported in [9] that allows different correlation levels in failures based on the traces. In [10], the reliability of a grid-computing system is evaluated considering the failure correlation of different subtasks executed by the grid; component failures are assumed independent, however. Moreover, a framework for modeling software reliability based on Markov renewal processes has been reported in [11] and [12] that is capable of incorporating the possible dependencies among successive software runs. None of the works above discuss the propagation of the correlated behavior such as node failures and their effects on survivability. In this work, we take epidemic model as a basis of node propagation to show node's correlated behavior. The works [13] and [14] are relevant to this work as they characterize the spread of correlated failure due to misbehave nodes. While these papers consider both independent and correlated failures and their effects on network connectivity, however, they do not provide a systematic stochastic approach to model correlated node behavior to evaluate propagation rate of correlated behavior.

3. K-Correlated Survivability Model

In this paper, the network survivability is defined as its capability to keep contact with neighboring nodes to perform forwarding activity. The k -correlated survivability model, which is based on correlated node behavior and Semi Markov process, considers four states of node behavior namely cooperative (C), selfish (S), malicious (M) and failure (F) states [15]. The model is built in the following steps:

Step 1: build the correlated node behavior model

- Define node behavior transition using Semi Markov process with a state space $\Omega = \{C, S, M, F\} = \{b, a, c, d\}$. Let P_{ij} and T_{ij} be the transition probability and transition time from state i to j respectively, for $i, j \in \Omega$.
- Find the transition probability matrix (TPM) $\mathbb{P} = (P_{ij})$ and a transition time distribution matrix $\mathbb{F} = (F_{ij}(t))$. $\mathbb{P} = (P_{ij})$ and $\mathbb{F} = (F_{ij}(t))$ are given by:

$$\mathbb{P} = \begin{pmatrix} 0 & a & c & d \\ b & 0 & c & d \\ 0 & 0 & 0 & d \\ e & 0 & 0 & 0 \end{pmatrix}, \quad \text{and}$$

$$\mathbb{F} = \begin{pmatrix} 0 & F_a(t) & F_c(t) & F_d(t) \\ F_b(t) & 0 & F_c(t) & F_d(t) \\ 0 & 0 & 0 & F_d(t) \\ F_e(t) & 0 & 0 & 0 \end{pmatrix} \quad (1)$$

where $F_x(t)$ is the cumulative distribution function (CDF) of T_{ij} for $i, j \in S$ and the transition probability matrix \mathbb{P} describing a chain is $N \times N$ matrix. The state transition diagram of semi Markov node behavior

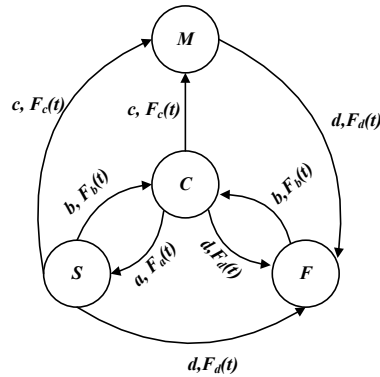


Fig. 1. Semi-Markov Process for Node Behavior

- Derive the steady-state transition probability distribution $\tilde{\pi}$ by solving the following set of equations:

$$\tilde{\pi} = \tilde{\pi}P \tag{2}$$

$$\sum_{i \in S} \pi_i = 1, \quad \pi_i \geq 0$$

Then, calculate the steady-state probability π_i of the node staying in transmission radius r :

$$\pi_i = \frac{\pi_i E[T_i]}{\sum_j \pi_j E[T_j]} \tag{3}$$

Step 2: Weighted function as a correlated degree

- Define an appropriate representation in term of a weighted undirected graph $G = G(V, E)$ as in Fig. 2, where V denotes the vertex set with $|N| = N$ and an edge E exists between two vertices only if their distance is no greater than r with the weight function $P : E(G) \rightarrow \omega$, interpreted as the probability of the edge being connected.
- Each edge $(u, v) \in E$ is associated with weight function $\omega(e)$ which represent infection rate $\beta_{uv}^s, \beta_{uv}^m$, or remove rate λ_{uv}^s or λ_{uv}^m . The model also allows node to join the network after node recovery with δ_{uv} . The weight functions of node u can be subsequently computed using equation :

$$\beta_{u,v} = \sum_{i=s,m} \pi_i^u \pi_i^v \tag{4}$$

$$\lambda_{u,v} = \sum_{i=c,s,m} \pi_i^u \pi_i^v \tag{5}$$

$$\delta_{u,v} = \sum_{i=s,f} \pi_i^u \pi_i^v \tag{6}$$

where π_i^u is the percentage of the time spend by node u in state i .

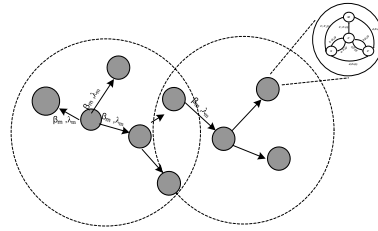


Fig. 2. Network Model with correlated node behaviour

Step 3: Calculate the probabilistic k -correlated survivability

- Survivability is evaluated based on probability of k -correlated in the presence of correlated behavior. We refer k as a positive integer of minimum number of edge such that the graph becomes disconnected if it is deleted. Thus, network survivability is said to be k -correlated if and only if any pair of two nodes there exist at least k mutually dependent edges connecting them.
- Based on undirected weighted network model in Fig. 2, for nodes to get connected, the edge connectivity must satisfy the following requirements:

$$\omega(u, v) = \omega(d_{uv}, \leq d_{max})$$

$$\omega(u, v) \geq \delta_{uv}, \text{ if and only if } \vartheta_u, \vartheta_v \text{ are adjacent in } (G, \omega).$$
(7)

where d_{uv} is the Euclidean distance between u and v , and δ_{uv} are the forwarding capacity of node u and v .

- Let ω_u denote the correlated degree of $N_u \in E(G, \omega)$, that is calculated using equation (4-6) in step 2 above. Given the correlated degree of node $\omega(u) \geq \delta$ then node u is connected to the network, and if otherwise node u is isolated from the network. Probability of node being isolated denoted by

$$P_{sm} = \omega(u) < \delta | \omega(u) = \delta$$

$$= P(n_{sm} + n_f) = \delta | \omega = \delta$$

$$= 1 - (1 - b)^\delta$$
(8)

- Given a network G with N nodes $N \gg 1$ and a connectivity requirement ω , let P_{sm} denote the probability of node being misbehave and isolated, and μ denote the average number of nodes within one nodes transmission range, then the k -correlated survivability of G is approximated by

$$S_{uv}(w, G) \approx \left(1 - \frac{\Gamma(w, \mu(1 - P_{sm}))}{\Gamma(w)} \right)^N$$
(9)

4. Survivability Analysis

In this section, we verify the correctness of our correlated node behavior theory on the network survivability. In simulation, all network parameters are set to the default value given in Table 1 below. Next, we explain our simulation results.

Table 1. The network simulation set up

Parameter	Setting
Simulation area	1000 m x 1000 m
Transmission range	100 m
Mobility model	SMS model (uniform placement)
Movement features	Avg. speed 4 m/s/ pause time 1 s
Link capacity	CBR (64 bytes)
Traffic load	100 connections, 8 packet per sec
Simulation time	10 s

4.1 The effects of cooperativeness of correlated nodes

As explain above, correlated degree is represented by edge connectivity ω . The higher the ω , it implies that the node is strongly connected. To observe the effect of correlated degree ω , we set $\delta = 0.7$ for cooperative threshold. Fig. 3 shows the analytic results of survivability under different edge connectivity $k=1, 2, 3$. It is observed that survivability incline steady line with fewer nodes. This is due to the misbehavior node effect are less. Thus, the effect of node behavior is tractable with fewer nodes. Cooperative nodes are affected by correlated degree ω to obtain a higher survivability. Thus it is necessary to have a higher packet forwarding rate of δ for cooperative degree δ for network to survive.

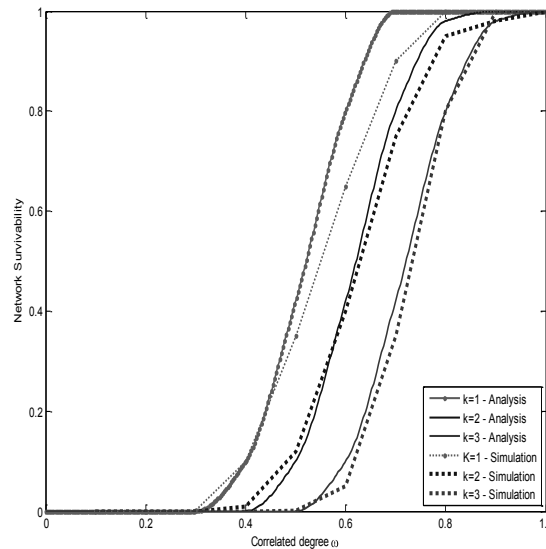


Fig. 3. Effect on survivability of cooperative Nodes

4.2 The effect of correlated misbehvae nodes (selfish and malicious)

Similar to that in Fig 3, the plot in Fig. 4 shows that the survivability decreases as β increase. It shows that more and more nodes are affected by the attacks and cause the network survivability to decrease. The survivability does not change significantly at the beginning especially if network scalability is less. In contrast, survivability for fewer nodes starts to decline faster compared to networks with large nodes. Network also becomes unstable when β more than 0.3. This shows that the misbehave node threshold has triggered to neighboring nodes and cause network to isolate or failed. From Fig 4 the network survivability decreases very fast due to the packet loads increase. This is due to nodes behave maliciously and disconnected from the network and thus the load originally routed to the node will be redistributed to neighboring nodes which cause chain reaction. This cause the node cluster will be isolated from the giant network as explain in equation (8) above. It also can be seen that network with more nodes could not sustain it survivability when network under attacks.

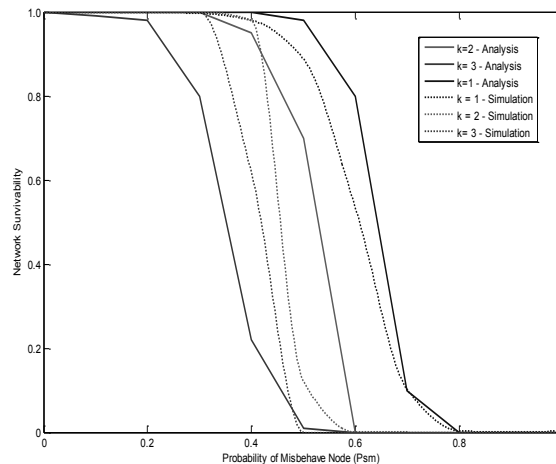


Fig. 4. Effect on survivability of node isolation P_{sm}

5. Conclusion

In this paper, we studied the problem of network survivability from a correlated node behavior perspective. We focused on ad hoc networks modeled by undirected weighted graphs. To analyze practical situations where node behaviors in the network are correlated, we investigated correlated degree based on epidemic theory on undirected weighted graphs on malicious and selfish attacks. An analytical model is developed to study the impact of correlated node behavior on network survivability, which is defined as the probabilistic k -correlated of the network. We derived the approximation of the network survivability by using an edge connectivity function ω as a correlated degree. In conclusion, the impact of node behaviors on network survivability can be evaluated probabilistically from equation (9) which can be further used as a guideline to design or deploy a survivable of mobile ad hoc network given a predefined survivability preference.

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