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Reliability evaluation of time evolving Delay Tolerant Networks based on Sum-of-Disjoint products

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ABSTRACT

Network reliability evaluation of Delay Tolerant Networks (DTNs) is a challenging task due to their inherent features like node mobility, dynamically changing network topology and existence of highly disruptive environmental conditions etc. The research so far on such time-evolving dynamic networks mainly focusses on topology control, routing and information propagation with a little attention paid towards computing their overall network reliability. In this paper, we model DTNs by using *Time Aggregated Graph* and propose the notion of *time-stamped-minimal path sets* between a given source-destination pair of nodes, besides, providing a simple yet novel method to enumerate them. Further, by employing Multiple Variable Inversion-Sum of Disjoint Products algorithm, we obtain disjointed *time-stamped-minimal path sets*, which have a one-to-one mapping with the overall reliability expression of such time evolving networks. For obtaining instances of a DTN during an operational period, we resort to Monte Carlo Simulation to simulate the dynamically changing topology and other probabilistically varying network aspects. The simulation results demonstrate the efficacy of our proposal. At the end, we also present some initial investigation and insight on the *time-stamped-minimal cut sets* and problem in enumerating them, and infer that the usual notion of cut sets seems inapplicable for dynamic networks.

1. Introduction

Delay Tolerant Networks (DTNs) are gaining immense popularity amongst the researchers at present due to their widespread and prospective applicability in adverse communication scenarios such as battlefield reconnaissance, space communications, mobile social networks and sensor networks, where a traditional communication infrastructure is either unavailable, infeasible or incapacitated for a long time.

DTNs customarily utilize *opportunistic networking* and *store-carry-forward* mechanism as there is an intermittent connectivity, time varying topology, high mobility, long delays and lesser number of nodes in the network in comparison to the mobile ad-hoc networks (MANETs). Specific examples of some delay tolerant services include updates on social networking websites, emails, firmware and software updates, cloud services, etc. In DTNs, information is propagated using the opportunistically existing and time varying routing paths as it is quite likely that two nodes may never be connected directly (end-to-end) but they are still capable to communicate with each other within a finite time horizon [1].

Several attempts have successfully been made to exploit the distinguishing features mentioned above in modeling and analyzing DTNs for reliably propagating the information throughout the network [2–4]. However, to the best of our knowledge, most of these works focus towards increasing the delivery probability, reducing latency, controlling topology, routing and minimizing the energy consumption and thus maximizing the network throughput without giving an explicit emphasis on the terminal or overall network reliability.

Conventionally, for any arbitrary infrastructure based network, the *network reliability* is defined as the probability that a specified set of designated nodes are able to communicate with each other within the intended design features and environments. Depending on the number of nodes in the specified set, the network reliability can be termed as *2-terminal, k-terminal* or *all-terminal reliability*. Note that *k-terminal reliability* measure could be termed as a generalization as $k = 2$ indicates *2-terminal reliability*, whereas $k = n$ (all nodes of the network) would yield *all-terminal reliability* of the network [5].

Another way of defining *2-terminal reliability* is that it is the probability that at least one *minimal path set* exists for a successful communication between a specified pair of nodes, *viz., Source-Destination* (*S-D*) pair. A *path set* between a specified (*S-D*) pair of nodes is said to be minimal if in that *path set*, no node or intersection between links is traversed more than once. If all n nodes are able to communicate with each other while the *path set* has a tree like structure (known as a spanning tree) then the network reliability is termed as *all-terminal reliability*. If a *path set* form a tree like structure where k-nodes out of the total of n nodes

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Notation

Cart	valid Cartesian product of time stamps
$i^{\{t\}}$	i-th link of the network along with its activity time stamp t
I	number of iterations
n	number of nodes
K_n	a complete graph of n nodes
nLi	maximum number of possible links in a graph of n nodes
newpath	valid minimal path sets
P	link formation probability
Q_{MH}	unreliability for multi hop transmission
R_{MH}	reliability for multi hop transmission
R_{SH}	reliability for single hop transmission
(S-D)	Source-Destination pair
T	number of time instants
TP	communication probability of each link

of the network are able to communicate with each other, the network reliability is known as *k-terminal reliability* [5].

The notion and terminology of the network reliability stated above can be extended to DTNs as well. For example, what will be the terminal reliability of a DTN consisting of n mobile nodes for a successful data transmission, where links and nodes are prone to failures? Here, we take time varying features of DTN into consideration and model such a time evolving DTN as a space-time graph, including both spatial and temporal information. We also assume that the underlying connections are non-deterministic; therefore, links among various nodes of the network are formed in a probabilistic manner following certain criteria. At any instant of observation time, the snapshot of this time-varying network can be considered as a static network graph. We show that the proposed model is capable of capturing both single-hop and multi-hop transmission features. This proposed model can also effectively represent the buffered information, which can be transmitted in some other time slot whenever an opportunity exists. The information might be needing buffering at nodes primarily due to the inability of a node to transmit the data owing to an ongoing transmission between the specified nodes and/or due to failure of nodes or links in the minimal path sets during an observed time slot. Although, in this paper, we only consider *2-terminal reliability*, and extend the definition of minimal path sets to *time-stamped-minimal path sets* yet the notion presented in this paper can easily be extended to other form of reliability measures. Further, we model the same DTN with Time Aggregated Graph (TAG) and propose an algorithm for evaluating all *time-stamped-minimal path sets* between any (S-D) pair in DTNs, whereby any Sum of Disjoint Products (SDP) algorithm such as [6] can be employed to generate network reliability expression and compute the reliability of such time evolving networks more accurately thereafter.

The remaining paper is organized as follows: In Section 2, we highlight the work related with modeling of time varying networks. In Section 3, the space-time graph based DTN model is defined for both single-hop and multi-hop transmission scenarios. Section 4 presents (S-D) pair based *time-stamped-minimal path sets* and reliability evaluation algorithm. Section 5 presents details on performance evaluation. In Section 6, a preliminary investigation on the viability of *time-stamped-minimal cut sets* is presented. Finally, concluding remarks along with the future scope of this research is presented in Section 7.

2. Related works

2.1. Modeling dynamic/time varying networks

Graph theory has been a boon for solving many complex engineering problems, and solving problems of reliability engineering through its extensive use is not an exception. The reliability evaluation of a flow-network or delay network also falls in this category. The changing topology of a network such as MANET or DTN further makes the problem more complex. However, the addition of time-labeling (or time stampings) of a link to indicate its existence in a dynamically changing scenario/network can make predictions and mechanistic understanding of dynamic networks more plausible and accurate. In the literature, many researchers have independently used the terms such as *evolving graphs, temporal graphs*, and *time-dependent networks* for models of dynamic networks. The evolving graph based modeling of dynamic networks like DTNs, Vehicular Ad Hoc Networks (VANETs), and Flying Ad Hoc Networks (FANETs) is becoming extremely popular now-a-days. Authors of [7] integrated the existing models, concepts and results of such synonymously used terms for dynamic networks into a unified framework and termed it as *Time-Varying Graphs* (TVGs). Using it, it is possible to express directly in the same formalism not only the concepts common to all these different areas but also those specific to each. This, in turn, should enable the transfer of results from one application area to another.

In a tutorial article, Ferreira [8] described a simple but powerful combinatorial model that captures most of the characteristics of a time varying network with its immediate applications in the topology control of MANETs. Their research focused on the design of models and algorithms that can harness the complexity of evolving environments. The networks, which can be modeled as TVGs, are omnipresent now-a-days, *e.g.*, human proximity networks, animal proximity networks, human communication networks, collaboration networks, citation networks, economic networks, brain networks, travel and transportation networks, distributed computing, biological networks, MANETs, DTNs, VANETs and Opportunistic Mobile Networks (OMNs) [9]. However, the current state-of-the-art for studying such networks still appears to be at its infancy stage because:

1) The inclusion of time in the network brings new constraints into picture, which demands further research efforts for their modelling and performance analysis and
2) The available analytical techniques for network reliability analysis have mainly been developed for static networks and are not suitable to apply them directly on TVGs without resorting to their substantial modifications.

In the literature, various representation styles have been developed to analyze TVGs. In Fig. 1, we summarize the major representation styles currently in vogue for the TVGs and briefly describe them for the sake of completeness.

Usually, the links in a TVG are represented in the form of lists of contacts, *i.e.*, a pair of nodes between which a link exists accompanied by the timestamp, indicating the instant at which that link had been active within an observation interval. This timestamp can either be on a discrete or continuous time interval. Another simple approach of TVG representation is to represent them as a *sequence or layers* of static network (Fig. 2). This is a viable approach mainly for networks with discrete times of contacts. *Time series of contacts* on a static graph *(time-aggregated graphs (TAGs))* is another representation style [9], which includes all the temporal information about the TVG in a single graph as shown in Fig. 3(b) for the complete network graph K_5 shown in Fig. 3(a). It includes a complete list of time of contacts between each node pair, wherever a link existed at any time instant within the observation interval. For instance {1, 2}, 1 indicates link #1 existed at time instants 1 & 2 within the observation interval of four time units. Authors of [9] also provided a simple representation of TVG as a *time line of contacts*, where one dimension represents time and other represents the set of nodes. Another deterministic model of TVG named as *temporal graphlets* similar to a time series of static graph snapshots and two different metrics, *viz., Store or Advance (SoA)* and *Cut-through (CuT)* to study latency are proposed in [10]. In the former, a message can be forwarded to only a neighbor in a unit time step, whereas in the latter, a message can be