On the Spatial-temporal Reachability of DTNs

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Abstract. As traditional "Connectivity" concept from the Internet ignores the possibility of opportunistic contacts in DTNs, this paper brings time dimension into consideration, proposes Spatial-Temporal Path, Spatial-Temporal Reachability and K-Reachability in order to better describe the whole communication process and "Eventual Transportability" of DTN. Analytical and simulation results are given to show the correctness of our approach. Furthermore, Spatial-Temporal Reachability and K-Reachability, which tell a network's robustness in a quantitative fashion, are proved to be suitable for analyzing efficiency and routing performance of DTNs.

Keywords: DTN, Connectivity, Spatial-Temporal Reachability.

1 Introduction

Delay/Disruption Tolerant Networks, known as DTNs[1, 2] and DTMNs[3] are some typical cases of challenged network[4, 5], which is defined as a network that possesses one or more of the following characteristics: high end-to-end path latency, intermittent connection between nodes, or the absence of an end-to-end path from sources to destinations. In such situations, TCP, usually used in traditional Internet communication, faces great challenges when dealing with DTNs' highly dynamic fashion[6]. Therefore, in a set of new protocols called Bundle, researchers came up with a "store-carry-forward" strategy[1, 2, 7-9]. A forwarding node carries messages before getting the "opportunity" to forward them. This strategy enables the message to be delivered successfully in a given time in a DTN environment. By using Spatial-Temporal routing[10], the communicating process of DTNs is characterized as opportunistic contacting[11].

Traditional "Connectivity" concepts in relation to the Internet focus on the end-to-end path between a pair of nodes for an instant time. In order to better understand

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the “Eventual Transportability” of a communication process in DTNs, we can see from Fig 1: node0, node1, node2 are fixed nodes, while node3 moves clockwise. Node3 establishes wireless communication links with node 0,1,2 separately during times 1, 2, 3.

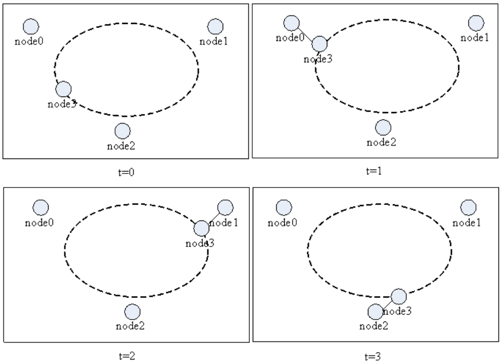

Fig. 1. A typical communication process in DTN

In above communication process, a message “path” is established for any node pair. Through this path, a message can be successfully transferred between any two nodes during a given time. This communication process tells us that the traditional “connectivity” concept mainly focuses on the static topological graph, while a static graph is not enough for describing the whole communication process and the “Eventual Transportability” of DTNs.

To our knowledge, the store-carry-forward fashion of challenged networks cannot be well described by known graph theory or other mathematical tools. In this paper, we bring time dimension into graph theory in order to form a Spatial-Temporal graph. “Spatial-Temporal Reachability” is proposed to describe the probability of a message reaching its destination in a given time in DTNs. Spatial-Temporal Reachability is a key concept of studying a communication system’s delivery ratio, robustness and efficiency.

The rest of this paper is organized as follows: Section 2 gives the related works on both multi-hop networks and DTNs; Section 3 presents environment and definitions for the key elements of Spatial-Temporal Reachability; Section 4 gives the Spatial-Temporal Reachability analysis process and results; in Section 5, we compare the simulation results with the analytical results; some discussions and conclusions are given in Section 6.

2 Related Works

In this section, recent works on “connectivity” regarding both multi-hop wireless networks and DTNs are introduced. In the area of traditional multi-hop networks, Christian Bettstetter[13, 14] et al. have studied a basic concept of Ad Hoc networks: its

K-connectivity. The probability for the K-connectivity of an Ad Hoc network is derived using only local information such as node numbers, the radio transmission range and node density. “Connectivity” in DTNs is more challenging owing to its intermittent connection and absence of end-to-end paths between nodes. Some researchers investigated the “connectivity” issue by employing Evolving Graphs[14], Contact Graphs[15], Multi-graphs [16] and Social Graphs[17]. Vincent Borrel et al.[18] proposed a space-time path in order to form an evolving graph. They developed an algorithm which can classify current DTNs based on information regarding node contacts. They also analyzed the impact on different DTNs of mobility parameters using two mobility models: Random Way Point Model[19] and Random Walk Model[20]. Contact Graph is proposed by Rugved Jathar et al. in 2010. The author developed a probabilistic routing protocol based on Contact Graph. The probability of nodes acquiring contact with each other is illustrated by Contact Graph in order to enhance efficiency of routing. Multi-graph is introduced by Kevin Fall et al. in ACM SIGCOMM in 2004. They try to model the routing process of DTNs as a multi-graph with time t as a variable. Multi-graph brings time t as a variable in order to describe a communication process. Social Graph is proposed by T Hossmann et al. in INFOCOM 2009. The authors argue that in most current challenged networks, connections of nodes are not entirely random.

3 Environment and Definientia

We introduce a Spatial-Temporal Graph to describe DTN and its “store-carry-forward” communication fashion. By bringing time dimension into consideration, a sequence of graphs labeled by time is proposed. With this approach, a dynamic DTN can be described as a sequence of static graphs changing over time.

Definition 1: The Spatial-Temporal Link $e_{v_i,v_j}(t_n)$ between node v_i and v_j at time t_n is,

$$e_{v_i,v_j}(t_n)=\left\langle v_i, v_j, t_n \right\rangle; i, j, n \in N;$$

Definition 2: The Spatial-Temporal Path $Path^T_{v_i,v_j}$ is a sequence of Spatial-Temporal Links within the Message Life Time T. The store-carry-forward technology passes a message along a Spatial-Temporal Path in order to complete a communication process,

$$Path^T_{v_i,v_j} = \left\langle e_{v_i,v_j}(t_n) \right\rangle; i, j, n \in [0, N], t_n \le T;$$

Definition 3: The Spatial-Temporal Reachability $Reachability(G(t),T)$ denotes the property of a Spatial-Temporal Graph being Spatial-Temporal reachable, which means a Spatial-Temporal Path between any pair of nodes always exist in Message Life Time T,

$$\begin{cases} Reachability(G(t),T) \to \forall i \forall j \exists Path^T_{v_i,v_j} \wedge t \le T; \\ i, j \in N, i \ne j; \end{cases}$$

Definition 4: Spatial-Temporal Reachability Degree $K-Reachability(G(t))$ is the degree of a Spatial-Temporal Graph being Spatial-Temporal reachable. If there exist K path-disjoint Spatial-Temporal paths between any node pair, we call the Spatial-Temporal Graph to be K-Reachable,

$$K-Reachability(G(t)) \rightarrow$$
$$(\forall i \forall j \exists Path^{T}_{v_i,v_j}) \wedge Number(Path^{T}_{v_i,v_j}) = K;$$
$$i, j, K \in N, i \neq j.$$

With the definitions on Spatial-Temporal Reachability and Spatial-Temporal Reachability Degree, we bring time-dimension into the analysis of the Eventual Transportability for messages. Spatial-Temporal Reachability tells that a DTN is "Connected" in the time of validity, and Spatial-Temporal Reachability Degree tells how well a DTN is "Connected". Spatial-Temporal Reachability is a better concept of studying a communication system's delivery ratio, robustness and efficiency rather that traditional "Connectivity".

4 Spatial-temporal Reachability analyses

In analyzing Spatial-Temporal Reachability, we intend to get the overall message reachability of a set of mobility models of DTNs. Using Random Direction Model as an example, we adapt a method to get the probability of a Spatial-Temporal Graph being K-Reachable from some local information such as node transmitting range, mobility model and speed of node movement.

4.1 Overall Ideas

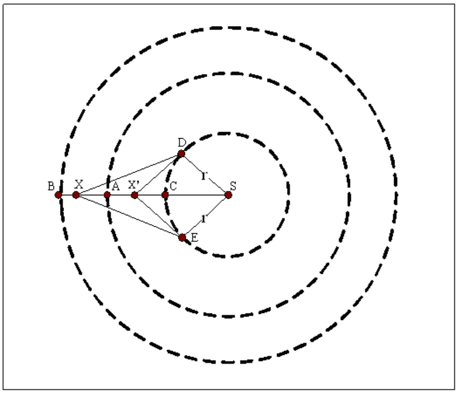

Fig. 2. Analysis of a two-dimensional random direction model

We use Random Direction Model[14, 22] as the mobility model for our analysis. V is the speed of movement for all the nodes in mobility model; r is the transmitting range for nodes; Message Life Time is set to T; total number of nodes is N. The number of neighbors (node degree) is a critical metric for a network. C. Bettstetter[12] gave a detailed analysis on the relationship between node degree and overall connectivity for a mobile network. He argues that a graph is said to be k–connected (k =1, 2, 3,...) if for each node pair there exist at least k mutually independent paths connecting them. In this paper, we follow this idea to calculate the paths each node has in order to get the overall Spatial-temporal Reachability for a DTN.

We first calculate the area size of the Contact Window ($CWindow$). In this window, nodes have the opportunity to move into the transmitting range of a certain node S within Message Life Time T; secondly, the probability for n of m nodes moving into S's transmitting range is acquired; while $n \le m \le N$, we get the probability for n nodes having Spatial-Temporal links with S in Message Life Time T , $P(X = n)$, and the probability for all the nodes having at least n Spatial-Temporal links in Message Life Time T, $P(X \ge n)$.

4.2 Spatial-temporal Reachability in a Two-Dimensional Mobility Model

The space distribution of a Random Direction Model in any time is uniform[13]. For a square map with area of S_{map} and a certain node S, we set pause time and reset time 0. The area size of ring BA and ring AC is S_{BA} and S_{AC}.
As shown by Fig. 2, we follow the analysis steps,

Step 1: Calculating the area of the Contact Window.

For any node A, it has to be located in the circle $S-(|V*T|+r)$ to get the opportunity of contacting S within time T. We firstly put nodes within circle $S-r$ out of consideration, and get the area of contact window,

$$CWindow = \pi\left(\left|V*T\right|+r\right)^2 - \pi r^2$$

Step 2: Probability of n of m nodes moving into S's transmitting range.

As Random Direction Model fits normal distribution, the probability for m nodes located in the Contact Window is

$$P(U^* = m) = C_N^m * \left(\frac{CWindow}{S_{map}}\right)^m * \left(1 - \frac{CWindow}{S_{map}}\right)^{N-m}$$

For node A, the moving direction has to be within $\angle MAN$ in order to get a contact with S (AM, AN are tangents to circle $S-r$). We derived the average angle for all the nodes that can contact S in the Contact Window,

$$\overline{\alpha} = \frac{S_{BA} * \alpha + S_{AC} * \alpha'}{2*\left[\pi*(r+V*T)^2 - \pi*r^2\right]}\ .$$

Through the average angle, we get the probability for n of m nodes moving into S's transmitting range in the Contact Window.

$$P(U=n)= C_N^m * \left(\frac{CWindow}{S_{map}}\right)^m * \left(1-\frac{CWindow}{S_{map}}\right)^{N-m} * C_m^n * \left(\frac{\overline{\alpha}}{\pi}\right)^n * \left(1-\frac{\overline{\alpha}}{\pi}\right)^{m-n} \tag{1}$$

We go back for nodes that were originally located in circle $S-r$. These nodes can contact S from time 0, so the probability for q of N nodes that communicate with S is

$$P(V=q)=C_N^q * \left(\frac{\pi * r^2}{S_{map}}\right)^q * \left(1-\frac{\pi * r^2}{S_{map}}\right)^{N-q} \tag{2}$$

Step 3: Probability for n nodes having Spatial-Temporal links with S

Based on (1) and (2), we get the probability for n nodes having Spatial-Temporal links with a certain node S,

Theorem 1:

$$P(X=n)=\sum_{i=0}^{n}\left(\left(\sum_{m=i}^{N} P(U=i)\right) * P(V=n-i)\right)=$$
$$\sum_{i=0}^{n}\left(\begin{array}{l}\sum_{m=i}^{N}\left(\begin{array}{l} C_N^m * \left(\frac{CWindow}{S_{map}}\right)^m * \left(1-\frac{CWindow}{S_{map}}\right)^{N-m} \\ * C_m^i * \left(\frac{\overline{\alpha}}{\pi}\right)^i * \left(1-\frac{\overline{\alpha}}{\pi}\right)^{m-i}\end{array}\right) \\ * C_N^{n-i} * \left(\frac{\pi * r^2}{S_{map}}\right)^{n-i} * \left(1-\frac{\pi * r^2}{S_{map}}\right)^{N-n+i}\end{array}\right)$$

From Theorem 1, we get the probability distribution of n nodes having Spatial-Temporal link with a certain node S within Message Life Time T:

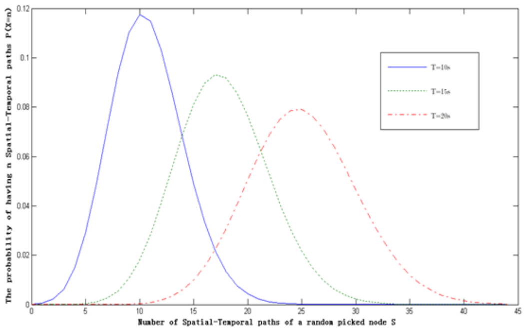

Fig. 3. Probability for all the nodes having n Spatial-Temporal links with a certain node S

1. *It shows that in T=15s, probability for all the nodes having 18 Spatial-Temporal links with a certain node S is 9% in analytical results;*
2. *When T=20s, analytical result shows probability for all the nodes having 26 Spatial-Temporal links with a certain node S is 8%.*

Step 4: Probability for the network being K-Reachable

Our goal is to get the overall reachability for the whole network. In Theorem 1 we acquired the probability for n nodes having Spatial-Temporal links with a certain node S. In a large scale network, events can be seen as independent from each other[13, 14]. As a result, when $N >> 1$, we finally get the probability for all the nodes having at least n Spatial-Temporal links, which means the network being K-Reachable:

$$P(X \geq n) = \left(1 - \sum_{j=0}^{n} P(X = j)\right)^{N} = \tag{3}$$

$$\left(1 - \sum_{j=0}^{n} \sum_{i=0}^{j} \left(\sum_{m=i}^{N} \left(\begin{array}{l} C_N^m * \left(\frac{CWindow}{S_{map}}\right)^m * \left(1 - \frac{CWindow}{S_{map}}\right)^{N-m} \\ *C_m^i * \left(\frac{\alpha}{\pi}\right)^i * \left(1 - \frac{\alpha}{\pi}\right)^{m-i} \end{array} \right) \\ *C_N^{j-i} * \left(\frac{\pi * r^2}{S_{map}}\right)^{j-i} * \left(1 - \frac{\pi * r^2}{S_{map}}\right)^{N-j+i} \right)\right)^N$$

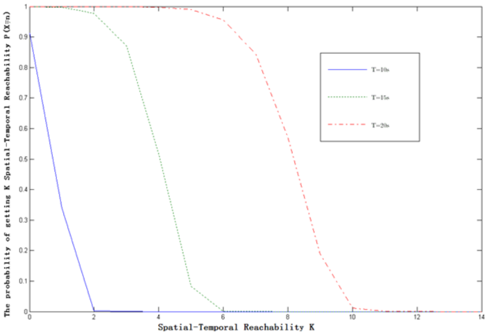

Fig. 4. Probability for the network being K-Reachable

With Message Life Time T=15s, analytical result shows probability for the network being 3-Reachable is 92%, while simulation shows 100%; when T=20s, analytical result shows probability for the network being 3-Reachable is 95%, while simulation indicates 100%.

5 Simulations and Discussions

In our simulation, we use C++ to build a Random Direction Model as an example for DTN simulation environment. For Random Direction Model, we set node number 1000, map size 2000m*2000m, node moving speed 20m/s, transmitting range 100m. We run the simulation 1000 times so that we can get the statistical distribution of n nodes having Spatial-Temporal links with a certain node S within Message Life Time T:

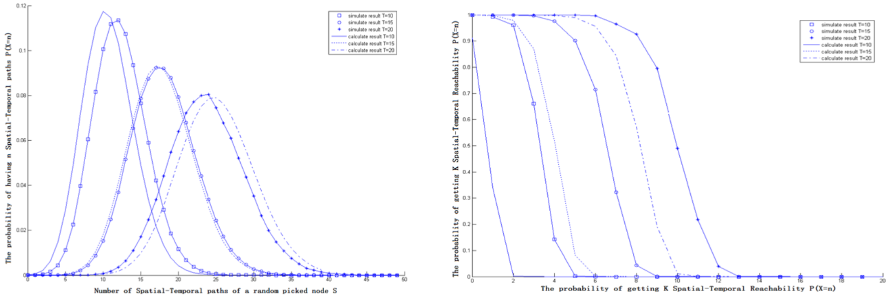

Fig. 5. Comparison for simulation results and analytical results

Fig. 5 shows that simulation results fit well with the analytical results. Probability for all the nodes having 18 Spatial-Temporal links with a certain node S is 9% in both analytical and simulation results; when T=20s, analytical results show that the probability for all the nodes having 26 Spatial-Temporal links with a certain node S is 8%, while simulation indicates 7%.

Fig. 5 also shows the probability for all the nodes having at least n Spatial-Temporal links (K-Reachability) in the two-dimensional Random Direction Model. We see that there are some differences between the analytical results and the simulation, the reason is that in our analysis process, we ignored the border effect, which can increase Spatial-Temporal Reachability when nodes bounce back to regain Spatial-Temporal links with other nodes. With Message Life Time T=15s, the analytical results show that the probability for all the nodes having at least 3 Spatial-Temporal links is 87%, while the simulation shows 100%; when T=20s, analytical results show that the probability for all the nodes having at least 6 Spatial-Temporal links is 95%, while the simulation shows 100%.

With the analysis above, we can get the probability of a network being at least K-Reachable for each Message Life Time.

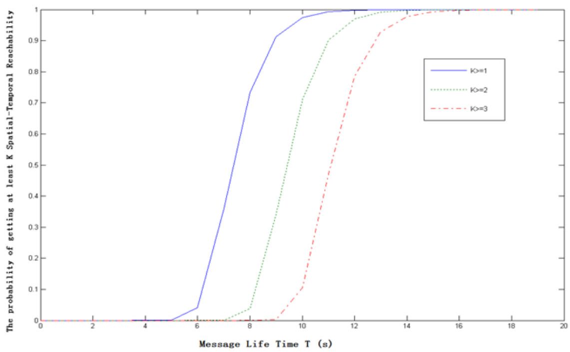

Fig. 6. Probability of a network being K-Reachability for each Message Life Time

In traditional MANETs, if a path to destination can't be found, the message will be dropped, which means Message Life Time is 0. However, a Spatial-Temporal path allows a message to be stored and carried by a node for a certain time T until being forwarded. From Fig. 6, when Message Life Time T=10s, the two-dimensional Random Direction Model has the probability of 97% to be at least 1-Reachability, 70% to be at least 2-Reachability and 10% to be at least 3-Reachability. K-Reachability offers more flexibility to describe a communication system, and can provide more Spatial-Temporal paths for delivering messages.

6 Conclusions

In this paper, we bring time dimension into graph theory to build a Spatial-Temporal graph. "Spatial-Temporal Reachability" is proposed to describe the probability of a message reaching its destination in time of validity in DTNs. Through mathematical analysis, we get K-Reachability for a network from some basic local information such as Message Life Time T, node moving speed V and transmitting range r. Simulations are also done to prove the correctness of our analytical results. By bringing time-dimension into consideration, we argue that Spatial-Temporal Reachability is a better concept of studying a communication system's delivery ratio, robustness and efficiency rather than traditional "Connectivity". Furthermore, we get the probability of a network being at least K-Reachable for each Message Life Time. Therefore, K-Reachability tells a network's robustness in a quantitative fashion, giving guidance to constructing high performance challenged networks. In the future, we plan to utilize our analytical approach in different mobility models, further applications of Spatial-Temporal Reachability are also considered.

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