Temporal Capacity Graphs for Time-Varying Mobile Networks

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ABSTRACT

With the rapid emergence of applications in mobile networks, understanding and characterizing their properties becomes extremely important. In this paper, from the fundamental model of time-varying graphs, we introduce Temporal Capacity Graphs (TCG), which characterizes the maximum amount of the data that can be transmitted between any two nodes within any time, and consequently reveals the transmission capacity of the whole network. By applying TCG to several realistic mobile networks, we analyze their unique properties. Moreover, using TCG, we reveal the fundamental relationships and tradeoffs between the mobile network settings and system performance.

Categories and Subject Descriptors

C.2.0 [**Computer-Communication Networks**]: General; C.4 [**Performance of Systems**]: [Modeling techniques, Performance attributes]

Keywords

Mobile networks, dynamic graph, transmission capacity.

1. INTRODUCTION

There is a rapid growth attentions for mobile network due to its wide applications[1]. In the mobile network, nodes may change locations, and therefore it has different network topologies at different time points[2]. The models of this kind of networks can be applied to many areas, such as modeling the flow of information through a distributed network and studying the spread of a disease through a population.

Over the past few years, time-varying graphs (TVG) has recognized as the fundamental model for mobile networks. However, different to the traditional static graphs, time-varying graphs perform dynamically and consequently more complex. Many of the usual concepts of static graphs have no obvious counterparts in dynamic ones. In the mobile network, the transmission contact of two nodes is opportunistic and the duration of contact is also random[3], and the data transmissions through these dynamical and random links/contacts are time-dependable and stochastic. As a result, it is difficult to observe the connectivity and even data transmission capacity of the networks directly from the TVG[4, 5, 6]. In the past work, much attention has been focused on to understand its connectivity [8, 9] and reachability properties [7, 10] while its capacity still remains unsolved and is lack of systematic theory.

Against the above background, we propose Temporal Capacity Graphs (TCG), which offers a immediate view of the capacity of mobile networks. In TCG, which is derived from TVG, the edges from nodes i to j at time t represents the maximum data that can be transmitted from i to j within delay δ through any multi-hop connected or opportunistic relays via a single path or via multiple pathes, where δ is the maximum delay tolerated by the data transmission. From TCG, we can further obtain the expected data transmission delay and delivery ratio that characterizes the network transmission capacity on some other hands. We obtain the TCGs of several mobile network simulated by realistic mobility traces. Consequently, we get the data transmission capacity and delivery ratio from the TCGs to offer a clear view of the mobile network, which is helpful for deciding some parameters. Through this, we reveal the fundamental relationships and tradeoffs between the mobile network settings and system performance.

2. SYSTEM MODEL AND TCG DEFINITIONS

2.1 Time-Varying Graphs

We first give a rigorous and clear definition for the TVG, and then introduce the concept of discrete-TVG.

Definition 1 (**Time-Varying Graphs**). *Let V be a set of vertices, and $E \subseteq V \times V$ be all the possible edges between vertices in V. For example, $e = (u, v)$ represents the edge from u to v. Let T be the time, and in this case, a TVG can be described as $G = (V, E, T)$ which contains all the information of a Time-Varying graph. Let $G(t)$ be a matrix which describe the connectivity condition at time t. $G(t)_{ij} = 1$ represents that edge from i to j exists at time t, and $G(t)_{ij} = 0$ represents that edge from i to j does not exit at time t.*

Definition 2 (**Discrete-TVG**). *Instead of considering continuous time, we divide time into pieces and each*

WWW'14 Companion, April 7–11, 2014, Seoul, Korea.
ACM 978-1-4503-2745-9/14/04.

piece has a length of η. During each piece of time, the TVG does not change. That is to say, $\forall k \in N, k\eta < t_1 \leq t_2 < (k+1)\eta \Rightarrow G(t_1) = G(t_2) = G(k\eta)$.*

2.2 Temporal Capacity Graphs

After we have the necessary background of TVG, we formally define the definition of the temporal capacity graphs for the single path and multipath respectively.

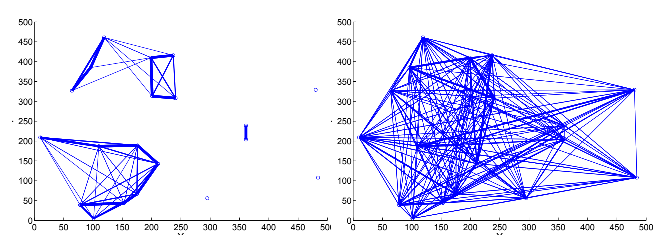
DEFINITION 3 (**Temporal Capacity Graphs**). *Considering D-TVG, for $\delta \in N^*\eta$, let $M_\delta(t)$ represents the TCG at time t. The value of $M_\delta(t)_{ij}$ represents the maximum data that can be transmitted from node i to node j between time t and $t+\delta$.*

3. PERFORMANCE EVALUATION

We used three human mobility traces. Two are TLW (Truncated Levy Walk) and SLAW (Self-similar Least Action Walk), which are the best models that describe human movement and we use the typical settings in [11]. For the TLW model, the Levy exponent for moving length and pause time distribution is set to be 1, and the minimum pause time is set to be 30s, the maximum pause time is set to be 3,600s, and the boundary condition is set to be wraparound. For S-LAW model, hurst parameter for self-similarity of waypoints is set to be 0.75, clustering range is set to be 50m, the Levy exponent for pause time is set to be 1, the minimum pause time is set to be 30s, and the maximum pause time is set to be 3,600s. For both of the two traces, we set the simulation network area as $500 \times 500m^2$. The third is real user mobility trace which records the communication between iMotes conducted during Infocom 2006 in Barcelona. IMotes were distributed to a group of people to collect any opportunistic sighting of other bluetooth devices (including the other iMotes distributed).

3.1 Performance of Mobile Networks

Fig. 1 shows the relation between the TCG and delay via single path. To make the result clear, we only depict the situation of parts of the edges and time. When δ is small ($\delta = 5$), most data is transmitted directly(happens when two nodes meet), and only a few edges can transmit data at several time points (about 20%). As δ=15, there are more indirect transmission, so the edges and time that can transmit data increase. When δ increases to 60, almost all the edges can transmit data at all time, which means that within $\delta = 60$, all nodes can communicate with others at any time and the mean data transmission is about 20MB.



(a)$\delta = 5$ (b)$\delta = 60$

Figure 2: Nodes connecting situation of different delay of TLW

Fig. 2 shows the connecting situation of nodes at a certain time t. The lines between nodes represent the data transmission ability at time t within delay δ, and the width of the line represents the amount of maximum data transmission. When delay is small($\delta = 5$), the nodes can be divided into several groups and nodes can only communicate within each group. However, if delay is big enough($\delta = 60$ or more), all nodes are connected. We generally want all the nodes in an area to be connected instead of several group. To achieve this, the network need to tolerant a certain length of delay so that all nodes can communicate with each other.

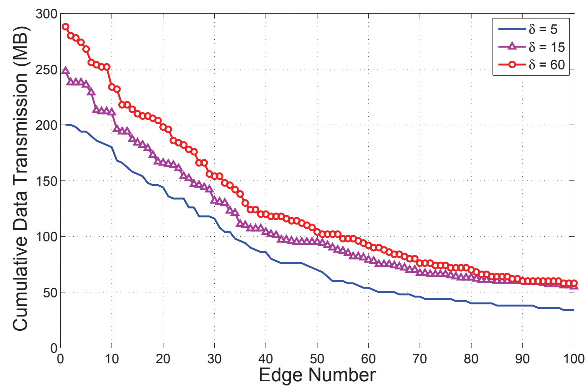
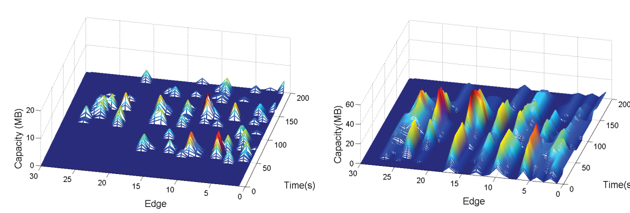


Figure 3: cumulative data transmission via single path of Real Trace of different delay

Fig. 3 shows the cumulative data transmission via single path of different delay. We obtain the result by dividing time into parts of length $d\eta$, and calculating the maximum data that can be transmitted during each part and add them up. We rank the edges from large to small by the cumulative data transmission and plot the first 100 edges. Since our simulation time is 300, we can see that when δ reaches 60 or more, the maximum cumulative data transmission is close to the simulation time, which means $\delta = 60$ is enough for the network to get well performance. Also, we can find that if δ is small($\delta = 5$), there will be a loss of about 30%. Besides, the the distributions of the three figures are almost the same. This means that the distribution of the network transmission capacity stays the same as δ changes.

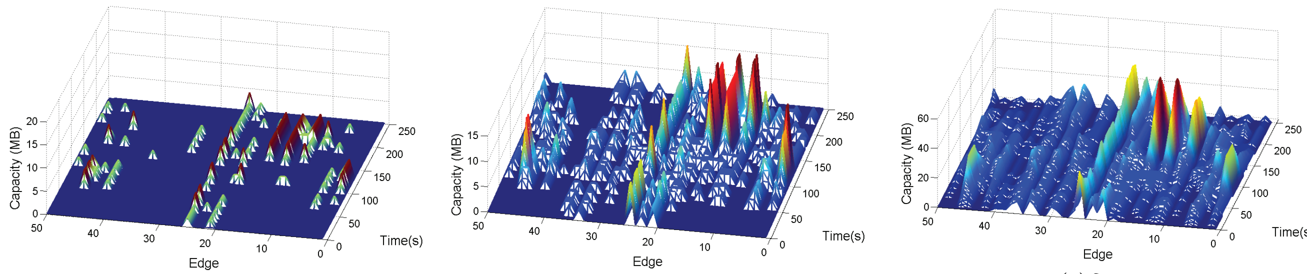


(a)$\delta = 5$ (b)$\delta = 60$

Figure 4: TCG via multipath of Real Trace of different delay

Fig. 4 reflects the relation between the TCG and delay via multipath. We get similar results as single path. We can also see that the performance is strongly influenced by delay and when δ increases to 60, the network will have well performance.

In this subsection, we mainly discuss performance of network using TCG and we can conclude that what we get is strongly influenced by the delay. From TCG, we can clearly



(a)$\delta = 5$ (b)$\delta = 15$ (c)$\delta = 60$

Figure 1: TCG via single path of different delay of Real Trace

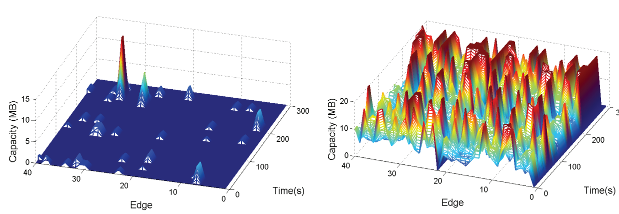
observe the connecting situation and transmitting ability of the network so it is easy for us to judge the performance of the network. In next subsection, we will investigate on the relation between some parameters and performance of network using the model of TCG.

3.2 TCG Applications

We now can get the TCG of a network if given the information. However, we are more interested in designing a network that we want. Since TCG reveals the property of a network, we can design and analyze the the network making use of TCG.

3.2.1 Communication Range

An important parameter is the communication range, which means the maximum distance for two nodes to communicate. For each two nodes, while their movements are decided, the lager the communication range, the more the probability of the data transmission.



(a)range=20 (b)range=200

Figure 5: TCG of different communication range of TLW

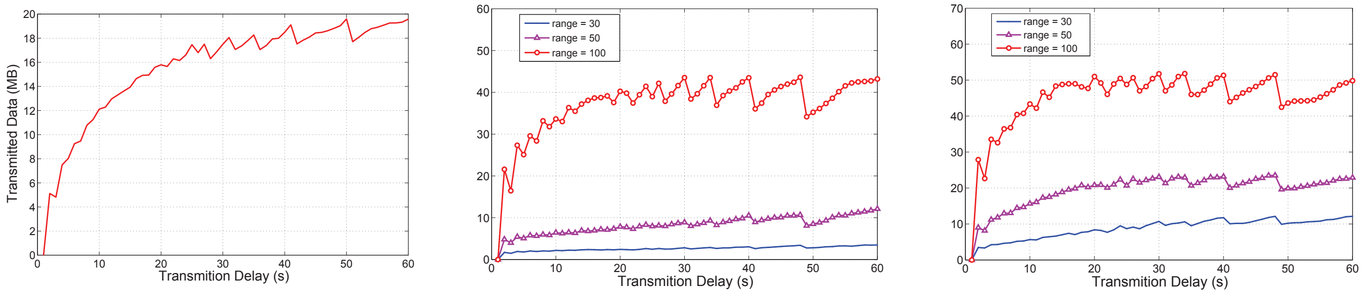
Fig. 5 shows the TCG via single path for a TLW model with different communication range. It is clear that the performance of network is strongly influenced by the communication range. We can see if communication range reaches 200, the network will have rather well performance that all nodes are connected with each other and can transmit considerable amount of data. We can conclude that increasing the communication range is a effective way to increase the capacity of a network. When the communication range increases by 10 times, the performance improves by 20 times. We can achieve this by using more powerful transmitter, reducing the interference of noise and increase the receiver sensitivity.

3.2.2 Delay And Data Size

In our analysis before, we do not consider data size. In fact, each time we communicate, the data has a certain size. Whether the communication can succeed depends on whether the maximum data transmission is large than the size of the data. Also, we generally want to send the data within delay δ and how long delay the network can tolerate is also an important factor for data transmission. If the network can tolerate long delay, we are more probable to transmit data successfully. Besides, we can also increase the probability of success by decreasing the size of data, such as dividing data into several parts and transmit them separately.

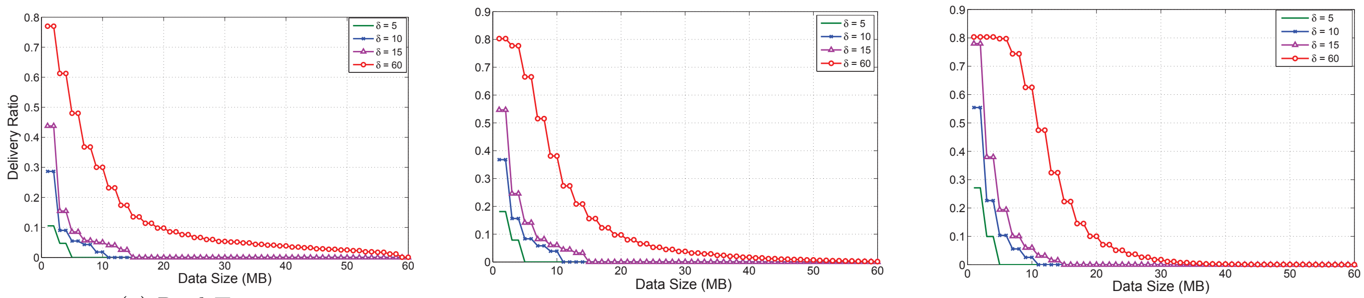
Fig. 6 shows the relative between mean data transmission and delay. We can see that for range = 100(TLW and SLAW), when $\delta > 20$, the increasing speed will decrease rapidly and the mean data transmission will not change much as delay increase. This indicates that the improvement by increasing delay is limited. If delay has already exceed the threshold, increasing delay will bring little improvement. Besides, no matter how long the delay is, the network cannot work if the communication range does not reach a certain value. For example, for TLW model, we can see that when range is less than 30, the mean data transmission is close to zero. When range increases to 50 or more, the maximum mean data transmission will increase to a considerable value. Also, when communication range increases from 50 to 100, the maximum mean data transmission will increase by 300%(TLW) and 100%(SLAW). Generally speaking, the maximum delay we can tolerant is a finite value δ. To get the best performance, we hope the threshold is larger than δ, so we need to set the communication range big enough to get the maximum data transmission.

The relation between delivery ratio and data size with different delay is shown in Fig. 7. In Fig. 7(a), the delivery ratio is increased from 10% to 80% when δ increases from 5 to 60. However, the delivery ratio decreases very fast as data size increases and for $\delta = 60$ the ratio decreases from 80% to 10% when size increases from 1 to 20. To achieve high delivery ratio(80% for example), the network generally needs a relatively large delay. For Real Trace and TLW, δ needs to reach 60 to achieve 80% delivery ratio while SLAW only needs 15, which can be explained as the meeting is more frequently or the range of motion is smaller. The delivery ratio is influenced by delay and data size. If we want to transmit data of fixed size with high success rate, we need to increase delay big enough. Similarly, if delay is fixed, then the size of data will be limited if we want to ensure delivery ratio.



(a)Real Trace (b)TLW (c)SLAW

Figure 6: Relation between the transmission delay and amount of transmitted data between each two nodes in time-varying graph characterized by our TCG in different mobility traces.



(a) Real Trace (b) TLW (c) SLAW

Figure 7: Relation between the data size and delivery ratio in time-varying graph characterized by our TCG in different mobility traces.

4. CONCLUSION AND FUTURE WORK

In this paper, we analyzed the capacity of mobile networks based on time-varying graphs, which gives a immediate view of the capacity of the network. Given TVG, we can calculate the maximum data transmission between each two nodes at any time t within any delay δ. Our work will be improved in several aspects. First, the calculation of the maximum data transmission can be further simplified. Second, in our paper, we come up with a lower bound of the maximum data transmission via multipath. A better approximation of the lower bound may exist and a upper bound may also be find. Finally, from the TVG, we may find other information except what we now get, and can better explain more fundamental property of the mobile networks and investigate how to utilize TVG in realistic mobile network design.

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