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Efficient multi-hop connectivity analysis in urban vehicular networks

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ABSTRACT

Vehicle to Vehicle (V2V) communication provides a flexible and real-time information dissemination mechanism through various applications of Intelligent Transportation Systems (ITS). Achieving seamless connectivity through multi-hop vehicular communication with sparse network is a challenging issue. In this paper, we have studied this multi-hop vehicular connectivity in an urban scenario using GPS traces obtained from San Francisco Yellow cabs. Our current work describes a new algorithm for the analysis of topological properties like connectivity and partitions for any kind of vehicular or mobile computing environment. The novel approach uses bitwise manipulation of sparse matrix with an efficient storage technique for determining multi-hop connectivity. The computation mechanism can be further scaled to parallel processing environment. The main contribution of this research is threefold. First, developing an efficient algorithm to quantify multi-hop connectivity with the aid of bitwise manipulation of sparse matrix. Second, investigating the time varying nature of multi-hop vehicular connectivity and dynamic network partitioning of the topology. Third, deriving a mathematical model for calculating message propagation rate in an urban environment.

1. Introduction

Over the past few years, connectivity in Vehicular Ad hoc Network (VANET) has been investigated by the researchers in different forms. One of the most common form of analysis is based on probabilistic modeling where some sort of simplified assumptions are made regarding the vehicular mobility pattern to determine the expected number of connected or reachable neighbors. This kind of analytical models show some properties of connectivity related to the overall traffic distribution and node density. Another type of analysis results from analyzing traces obtained from sophisticated vehicular traffic simulators where the robustness factor depends on the granularity of the microscopic mobility features. But still, this kind of microscopic mobility simulators fail even to capture the spatio-temporal variation of actual urban traffic. For this purpose, researchers are now more inclined towards utilizing real GPS trajectories from probe vehicles to capture the spatio-temporal characteristics of urban mobility patterns. But, problems still exist in this approach when the total number of probe vehicles are too small to be scaled to represent the mass traffic. However, if the number of probe vehicles is sufficiently large, for example if the entire fleet of public transportation or taxi cabs are within the monitoring scope, this can essentially resemble the spatio-temporal features of the real time mass traffic. In addition, the calculations of vehicular connectivity entail complex computation using chain matrix multiplications. For example, every single moment the positions of the nodes change and form a new topology resulting into a different adjacency matrix. Existing algorithms for determining broadcast propagation rate in a vehicular network only account for connected network. In order to estimate message dissemination delay beyond the connected component using a store and forward mechanism, the algorithm needs to keep track of the changes in network partition due to the mobility of the vehicular nodes. This requires a more sophisticated algorithm that is capable to keep track of the newly connected nodes at every distinct time slot. From this perspective, ours is the first attempt to develop a new analytical approach and computational method for vehicular connectivity analysis using Boolean Matrix Multiplication.

On the other hand, Boolean Matrix Multiplication (BMM) has long been a topic of interest among the theoretical computer scientists. While researchers [28–30] have been trying to utilize BMM to determine transitive closure of a network since early seventies of the last century, not much effort has been put on leveraging the techniques of sparse matrix multiplication with BMM. As from practical sense, most vehicular ad hoc networks are sparse.

Hence, using dense matrix multiplication algorithms to determine connected components or transitive closures is obviously

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inefficient. Our algorithm, apart from utilizing the techniques of sparse matrix multiplication, also considers an incremental approach for chain multiplication. This reduces the overall computational complexity for determining the transitive closure. Moreover, we reduce the storage cost by allocating only a single bit per each matrix element and increase the computational efficiency by incorporating bitwise operations on blocks of bits. We named this algorithm a Boolean Chain Matrix Multiplication (BCMM). From the perspective of vehicular communication and wireless networking, this is by far the first algorithm of this kind for analyzing multi-hop connectivity and network partitions.

It can be envisioned that in near future, enterprise business applications or commercial applications might be developed on top of DSRC platform targeting a particular class of vehicles in a specific geographical terrain. For example, a taxi cab company may use an internal fleetwide business application using V2V communication platform. Other examples of this type of selective multicast applications include commercial applications targeting vehicles of specific manufacturer or government entities trying to draw attention of a specific class of travelers, etc. Irrespective of the application scope, we present an efficient algorithm to determine the multi-hop connectivity within a large fleet of moving vehicles in a metropolitan area. We also described how this algorithm can be used to determine the network partitioning and broadcast propagation rate in a mobile taxi network. Our analysis results were based on live GPS traces obtained from the fleet of San Francisco yellow cabs [1]. The trajectories were made available through the Cabspotting project [3], a remarkable initiative of San Francisco Exploratorium [2]. The Cabspotting project is intended as a framework to help use the movement activity of commercial cabs to explore the economic, social, political and cultural issues that are revealed by the realistic GPS traces. Our analysis dealt with the entire fleet of 536 cabs generating over 10 million mobility traces within a period of one month. Our previous work [23] using these archived datasets showed interesting factors about taxi cab mobility, trip pattern, passenger hotspots, drivers empty cruise time and some basic analysis of data communication.

On the whole, majority of the prior researches on connectivity and partitioning were based on probabilistic modeling and simulating with mobility traces generated by well known traffic simulators, without using any real probe data or GPS traces. This makes our work different from all previous analysis. We also introduced the notion of saturated connectivity and a mathematical model to derive the message propagation rate in such a dynamic network. Our current work describes a complete method and step by step algorithm for the computation of topological characteristics in a highly dynamic environment. Moreover, ours is by far the first approach for determining multi-hop connectivity using sparse binary matrix manipulation with an efficient storage and computation mechanism. It has been already established by the researchers that the vehicular network can also act as a special form of Delay Tolerant Network (DTN) where information can be stored temporarily and forwarded as soon as a previously isolated node becomes reachable from a broadcasting node. Hence, in this way an emergency notification regarding traffic accidents or detour can be propagated throughout the entire urban metropoltan area. Here we investigated the propagation rate of such emergency messages within a taxi fleet covering a metro area. In addition, we also investigated the spatio-temporal behavior of network partitions and connectivity. The main contribution of this research is two fold. First, developing an efficient algorithm to quantify multi-hop connectivity with the aid of bitwise manipulation of sparse matrix. Second, investigating the time varying nature of multi-hop vehicular connectivity, dynamic network partitioning and message propagation in an urban environment. To the best of our knowledge, this is also the first approach to develop an efficient algorithm of this kind which can be further scaled to parallel processing environment for performance improvement.

The subsequent sections are organized as follows: we discuss related work in Section 2, followed by our system model and data collection methodology in Section 3. Section 5 presents the steps of the proposed BCMM algorithm preceeded by pre-processing of raw data in Section 4 and followed by applications of this algorithm in Section 7. Section 8 describes the details of results and analyses on vehicle connectivity and partitioning of the mobile nodes. Finally, we conclude in Section 9.

2. Related work

Several researchers came up with various algorithms and implementations of BMM [27–33]. Some of the recent researchers [27,34,35] introduced quantum computing based algorithm for BMM while some others [32,33,36] followed combinatorial algorithm. However, quantum computing is not implemented yet and still far from reality. The best combinatorial algorithm [36] so far gives the complexity of BMM bounded by $O(\frac{n^3}{\log^{2.25}(n)})$. Fischer and Meyer [28] theoretically showed that the upper bound of computational complexity for calculating transitive closure using BMM is $O(n^{\alpha}.P(n))$ where $\alpha = \log_2 7$ and $P(n)$ is the number of bitwise operations needed. However, this algorithm is based on dense matrix multiplication and do not consider the sparseness of adjacency matrix for real network. Our BCMM algorithm is an incremental approach of computing chain multiplications of adjacency matrix to generate the transitive closure and multi-hop connectivity in a dynamic vehicular network.

Even though vehicular connectivity problem is an interesting topic for the VANET research community, but not much work has been done from the perspective of analyzing network partitioning and multi-hop reachability using real world traces. However, several analytical models have been developed using traffic simulators that shows the relationship between transmission range and node connectivity. Ukkusuri and Du [16] derived an analytical lower bound of average reachable nodes to maintain high connectivity, obtaining a relationship between the total node size and average number of reachable nodes. However, their analysis was based on a particular segment of freeway using data obtained from MITSIMlab, which is a traffic simulation framework. In our current work, we also derived the average number of reachable nodes from each node with an additional constraint added on the forwarding delay which includes the queueing, storing, transmission and propagation delay in each hop. Our traces are obtained from GPS trajectories of San Francisco Yellow Cabs covering the entire metropolitan area.

Ho et al. [20] utilized the Groovenet traffic simulator to generate traces of structured mobility and provided an analytical framework to investigate the k-hop connectivity in vehicular network. The authors also demonstrated the impacts of macro and micro mobility features on k-hop connectivity. They defined some useful metrics to evaluate the node connectivity in vehicular networks.

Fiore and Harri [22] studied the effects of node mobility on the topology of a vehicular network through comparative analysis between some of the well known stochastic and traffic stream mobility models. Their research dealt with the duration of peer-to-peer wireless links, node degree, number of partitions or connected components, average partition size, etc., in different kind of mobility. It is worth to mention that, our analysis also encompasses most these metrics but using real GPS traces instead of software generated trajectories.

Ferreira et al. [17] developed a framework named 'DIVERT' for large-scale traffic simulation and computation of node connectivity in vehicular sensor network. Using the DIVERT framework, the authors have demonstrated the temporal evolution of the average