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Adaptive scheduling for real-time and temporal information services in vehicular networks

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ABSTRACT

Vehicular networks represent a research area of significant importance in improving the safety, efficiency and sustainability of transportation systems. One of the key research problems in vehicular networks is real-time data dissemination, which is crucial to the satisfactory performance of many emergent applications providing real-time information services in vehicular networks. Specifically, the two issues need to be addressed in this problem are maintenance of temporal data freshness and timely dissemination of data. Most existing works only considered periodical data update via backbone wired networks in maintaining temporal data freshness. However, many applications rely on passing vehicles to upload their collected information via wireless network, which imposes new challenges as the uplink data update will have to compete with the downlink data dissemination for the limited wireless bandwidth. With such observations, we propose a temporal information service system, in which vehicles are able to collect up-to-date temporal information and upload them to the roadside units (RSU) along their trajectories. Meanwhile, RSU can disseminate its available data items to vehicles based on their specific requests. Particularly, in this paper, we first quantitatively analyze the freshness of temporal data and propose a mathematical model to evaluate the usefulness of the temporal data. Next, we give the formulation of the proposed real-time and temporal information service (RTIS) problem, and prove the NP-hardness of this problem by constructing a polynomial-time reduction from 0–1 knapsack problem. Subsequently, we establish a probabilistic model to theoretically analyze the tradeoff between timely temporal data update and requested data dissemination sharing a common communication resource, which provides a deeper insight of the proposed RTIS. Further, a heuristic algorithm, namely adaptive update request scheduling (AURS), is designed to enhance the efficacy of RTIS by synthesizing the broadcast effect, the real-time service requirement and the service quality in making scheduling decisions. The computational complexity and scalability analysis of AURS is also discussed. Last but not least, a simulation model is implemented and a comprehensive performance evaluation has been carried out to demonstrate the superiority of ARUS against several state-of-the-art approaches in a variety of application scenarios.

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1. Introduction

Vehicular Networks represent the cornerstone of the envisioned intelligent transportation systems by enabling vehicles to communicate with each other as well as the roadside units (RSUs). They have been considered as one of the most promising techniques for providing safe, efficient and sustainable road traffic in reality Miloslavov and Veeraraghavan (2012). In vehicular networks, traffic information such as vehicle position, and traffic jams, is collected by vehicles and updated to the RSUs, which are sparsely distributed along the roadside. Simultaneously, these RSUs will provide time-sensitive and location-aware information to vehicles for a safer and more efficient driving experience. Clearly, maintenance of temporal data freshness and timely dissemination of data are challenging research issues in vehicular networks.

In the literature, many research efforts have been deployed for providing information services in vehicular networks. However, most existing works only considered periodical data update via wired backbone networks Peng et al. (2006), Zhou et al. (2011) and Liu and Lee (2012), which cannot support many emerging applications in vehicular networks such as real-time location-based services where information collection and update are performed by passing vehicles. On the other hand, few works have been proposed to consider the timely data update in vehicular networks and to improve the fresh data ratio maintained at the RSU. For instance, Zhang et al. (2007) defined a binary state (i.e., valid or not) to measure the freshness of data. Nevertheless, as it only has two levels of freshness, it often fails to cope with the case that freshness of data items changes gradually over time. Further, it is worth noting that in existing studies, a common assumption on information services is that a request only corresponds to a single data item and the request is satisfied as long as the data item is retrieved Xiang et al. (2015). This cannot meet requirements in many sophisticated applications such as real-time routing services, where multiple pieces of road information are required for computing the optimal route.

Today, with the rapid development of technology in wireless communications, new applications in vehicular networks, such as autonomous intersection control Lee and Park (2012) and Lee et al. (2013), road reservation Liu et al. (2013) and Edara and Teodorović (2008) and in-vehicle infotainment Tian et al. (2014), have emerged, where requests for real-time and multiple data items are always required. Further, in these applications, temporal information collected by passing vehicles is required to be uploaded to RSUs cooperatively, which imposes new challenges as the data update will have to compete for the limited wireless bandwidth against the data dissemination process. Thus, there is an appeal for novel solutions which can handle timely temporal information update and provide real-time request service for multiple dependent data items simultaneously.

Keep the above in mind, this paper considers a vehicular network, in which the RSU is installed at the road intersection to provide information services to passing vehicles via infrastructure-to-vehicle (I2V) communication Saad et al. (2011) and Shen et al. (2014). The temporal information is collected by vehicles along their trajectories and uploaded to the RSU when crossing the intersection. On the other hand, the RSU can broadcast data items to vehicles in an on-demand manner. There are stringent timing requirements on providing efficient data services in such a system, including both the timely data dissemination to serve real-time requests and the timely data update to ensure service quality, which will compete for the limited wireless bandwidth. Apparently, consuming excessive resources by one party will adversely impact on the performance of the other, and it is non-trivial to meet both requirements simultaneously. In view of this, this paper makes the first effort on scheduling real-time and temporal information services in vehicular networks by striking a balance between updating temporal data items and serving real-time requests to achieve the best overall system performance. It is noted that this paper focuses on the scheduling issues at the application layer of the vehicular networks, which is quite different from the issues relied in lower layers (e.g. network layer, MAC layer, etc.). Specifically, this paper considers the data quality and the dependency issue of multiple data items in scheduling, which are application-specific.

The main contributions of this work are outlined as follows. First, we quantitatively analyze the freshness of temporal data and propose a mathematical model to evaluate the usefulness of temporal data. Subsequently, by considering the stringent requirements of real-time requests and temporal data, we formulate the real-time and temporal information service (RTIS) problem, which aims for efficient usage of wireless bandwidth of both data update and dissemination. The proof of the NP-hardness of the proposed RTIS is also presented by constructing a polynomial-time reduction from the 0–1 knapsack problem. Next, to provide deeper insight on the adaptive bandwidth allocation for data update and dissemination in a common wireless resource, we establish a probabilistic model to theoretically analyze the relationship between the enhancement of data quality and the improvement of request service ratio. On this basis, we further propose a heuristic scheduling algorithm, namely adaptive-update request scheduling (AURS), to enhance the overall system performance by considering the key factors including broadcast effect, real-time request requirement and data usefulness in making scheduling decisions. AURS is able to adaptively allocate bandwidth for data update and data dissemination in varying traffic conditions and application requirements. In addition, the scheduling overhead of AURS is analyzed, which demonstrates its feasibility and scalability. Last, we build the simulation model and implement the proposed algorithm as well as the most competing solutions in the literature for performance comparison. Simulation results demonstrate that the proposed algorithm significantly outperforms existing solutions under a variety of circumstances. To the best of our knowledge, this is the first work in vehicular networks that considers both temporal data update and real-time request service for multiple dependent data items in a shared wireless communication resource.

The rest of this paper is organized as follows. Section 2 reviews the related work. Section 3 presents the system architecture. In Section 4, we formulate the RTIS problem and in Section 5, we derive an analytical model. A heuristic scheduling