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Offloading mobile data traffic for QoS-aware service provision in vehicular cyber-physical systems

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HIGHLIGHTS

- A Wi-Fi and VANET offloading model is established and the offloading capacity is quantified.
- A multi-objective combinatorial problem for mobile data traffic offloading is formulated and optimized.
- The proposed offloading approach of Vehicular Cyber-Physical Systems (VCPSs) supports global QoS guarantee and service provisioning.

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ABSTRACT

Owing to the increasing number of vehicles in vehicular cyber-physical systems (VCPSs) and the growing popularity of various services or applications for vehicles, cellular networks are being severely overloaded. Offloading mobile data traffic through Wi-Fi or a vehicular ad hoc network (VANET) is a promising solution for partially solving this problem because it involves almost no monetary cost. We propose combination optimization to facilitate mobile data traffic offloading in emerging VCPSs to reduce the amount of mobile data traffic for the QoS-aware service provision. We investigate mobile data traffic offloading models for Wi-Fi and VANET. In particular, we model mobile data traffic offloading as a multi-objective optimization problem for the simultaneous minimization of mobile data traffic and QoS-aware service provision; we use mixed-integer programming to obtain the optimal solutions with the global QoS guarantee. Our simulation results confirm that our scheme can offload mobile data traffic by up to 84.3% while satisfying the global QoS guarantee by more than 70% for cellular networks in VCPSs.

1. Introduction

In recent years, vehicular cyber-physical systems (VCPSs) have been proposed to exploit the latest advances in sensing, computing, communications, and networking technologies to improve the intelligence, safety, efficiency, resiliency, and environmental compatibility of transportation systems [1,2].

With the rapid development of VCPSs, an increasing number of vehicles with wireless communication capabilities can connect to Wi-Fi or cellular networks, thereby gaining access to various mobile services or applications such as safety applications, driving assistance, and multimedia content sharing. Owing to the widespread use of vehicles and growing service demands, mobile data traffic is increasing at an unexpected rate in VCPSs. According to the latest Cisco forecasts [3], global mobile traffic will increase tenfold between 2014 and 2019, and monthly global mobile data traffic will surpass 24.3 exabytes by 2019. Because of this exponential growth in mobile data traffic, cellular networks will be overloaded. In particular, during peak-hour traffic in urban areas, service provision will suffer from extreme performance hits in terms of limited network bandwidth, dropped calls, and unreliable coverage.

Rapid growth in mobile data traffic leads to a sharp drop in the quality of service provision [4]. To provide effective quality of service (QoS), the most straightforward solution is to increase the cellular network capacity by adding more base stations with a smaller cell size, such as picocells and femtocells, or by deploying 4G networks [5]. Hence, service providers around the world are busy rolling out 4G networks to meet the growing end-user demand for better QoS such as higher bandwidth and faster connectivity on the go. However, although 4G or LTE networks

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provide better QoS, when vehicular capabilities are combined with these networks, the widespread adoption of advanced vehicular applications, such as video sharing, cloud applications, and big data services, will further increase mobile data traffic. For example, in 2013, a 4G connection generated 14.5 times more traffic on average than a non-4G connection [3]. Therefore, even if the capacity of existing networks is enhanced, the future demands of users and applications will quickly exceed the network capacity. Simply using cellular networks for vehicular Internet access may aggravate the overload problem and degrade the service performance of both non-vehicular and vehicular users [6]. Thus, rapid growth in mobile data traffic leads to a growing need for offloading solutions, and it becomes essential for operators to provide various offloading schemes in VCPSs.

There are two types of schemes for achieving mobile data traffic offloading: Wi-Fi offloading [5–7] and vehicular ad hoc network (VANET) offloading [8–10]. Cellular network congestion can be alleviated by delivering data originally targeted for cellular networks by Wi-Fi (*i.e.*, Wi-Fi offloading) [6]. It has been shown that approximately 65% of cellular traffic can be offloaded by merely switching from cellular networks to Wi-Fi when Wi-Fi connectivity is available [5,6,11]. In urban environments, vehicles with low mobility signal nearby Wi-Fi access points (APs) when traveling along a road so that cellular traffic can be delivered to the vehicles through the drive-thru Internet [12] in an opportunistic manner. This opportunistic Wi-Fi offloading offers unique features in VCPSs. At present, vehicles are ranked third, behind homes and offices, in terms of places where people spend the most time daily [13]. Moreover, vehicles are becoming increasingly intelligent and connected, as they are equipped with on-board units (OBUs). According to forecasts of the European Telecommunications Standards Institute [14], by 2027, nearly all vehicles will be equipped with OBUs. OBUs are devices that provide vehicle-to-vehicle (V2V) links and vehicle-to-infrastructure (V2I) communications, where Wi-Fi APs and base stations of cellular networks belong to the infrastructure. Moreover, a dedicated frequency band, 5.86 to 5.92 GHz, has been allocated for IEEE 802.11p vehicular communications. Therefore, considering VANET for offloading cellular traffic (*i.e.*, VANET offloading) represents an attractive solution.

Using the above-mentioned technology as a foundation, some notable studies [5–10] have focused on offloading mobile data traffic. Although these offloading schemes can significantly reduce the mobile data traffic in cellular networks, they are not sufficiently efficient for VCPSs owing to two factors. First, most current studies focus on Wi-Fi offloading or VANET offloading and assume homogeneous offloading capacity for each Wi-Fi AP and vehicle in VCPSs. At first glance, this assumption appears to be reasonable, but it is unreasonable in a VCPS environment because different vehicles or newly deployed Wi-Fi APs are usually added to VCPSs to provide services; thus, different vehicular and Wi-Fi configurations form a heterogeneous mobile data traffic offloading environment. Second, an excellent mobile data traffic-offloading scheme satisfies the maximum traffic offloading requirements for service provision and also guarantees QoS. Therefore, QoS also plays an important role in determining the success or failure of offloading schemes. However, traditional offloading schemes mainly focus on the local QoS guarantee of mobile data traffic offloading and rarely consider the global QoS guarantee of service provision. The local QoS guarantee of mobile data traffic offloading is to offload traffic from a node with its QoS requirements independently on the other nodes. Even if the local QoS guarantee approach is useful in Wi-Fi environments, it is not suitable for mobile data traffic offloading with end-to-end QoS constraints (*e.g.*, maximum total response time) because such global constraints cannot be verified locally. The global QoS guarantee approach aims at solving the problem on the composite mobile data traffic offloading level. The aggregated QoS values of all possible nodes from Wi-Fi or VANET are computed and the node combination that maximizes mobile data traffic offloading while satisfying global constraints is selected. Hence, finding a tradeoff between mobile data traffic offloading and the global QoS guarantee is very important for VCPSs.

In this paper, we propose an alternative mobile data traffic offloading approach for VCPSs. In contrast to the previous studies described above, our study removes the assumption of offloading capacity homogeneity and considers the global QoS guarantee of QoS-aware service provision. First, we establish the Wi-Fi and VANET offloading models and quantify the offloading capacity of each Wi-Fi AP or vehicle. Then, mobile data traffic offloading is formulated as a multi-objective combinatorial optimization problem that aims to simultaneously optimize possibly conflicting objectives. The objectives include making efficient use of multidimensional resources, satisfying the global QoS guarantee, and reducing mobile data traffic. A mixed-integer programming search method is used to efficiently search for global optimal solutions within a reasonable runtime. We implement our approach and compare it with the other approaches using the QualNet simulator.[1] The simulation results indicate that our approach significantly reduces mobile data traffic while satisfying the global QoS guarantee in VCPSs.

The remainder of this paper is organized as follows. Section 2 reviews related studies. Section 3 establishes the Wi-Fi and VANET offloading models for VCPSs, quantifies their offloading capacity, and presents the problem statement. Section 4 describes the proposed approach to mobile data traffic offloading for QoS-aware service provision in VCPSs. Section 5 presents performance evaluations for comparing our solution against existing solutions. Finally, Section 6 summarizes our findings and concludes the paper.

2. Related work

Some notable schemes have been proposed to provide efficient mobile data traffic offloading for VCPSs.

From the Wi-Fi offloading perspective, Wi-Fi is recognized as one of the primary offloading technologies [11]. P. Deshpande et al. [15] proposed a prefetching mechanism motivated by the effective prediction of the mobility and connectivity of vehicles; the data can be redundantly prefetched by subsequent Wi-Fi APs. Subsequently, L. Kyunghan et al. [16] presented a delayed offloading framework, whereby users specify a deadline for each application or data, and each delay tolerant data is served in a shortest remaining time first manner through Wi-Fi networks. If the delay deadline of the data expires, the data are transmitted through 3G networks. A. Balasubramanian et al. [17] proposed an offloading framework for vehicular networks that supports fast switching between 3G and Wi-Fi and avoids bursty Wi-Fi losses. C. Nan et al. [6] presented an analytical framework for offloading cellular traffic through outdoor Wi-Fi networks in the vehicular environment and then modeled the arrivals and fulfillments of data services of a vehicular user as an M/G/1/K queue, derived the probability distribution of the effective service time, and analyzed the average service delay and offloading effectiveness via queuing analysis. P. Lv et al. [18] proposed an approach to support seamless and efficient Wi-Fi-based Internet access for moving vehicles. It consists of innovative protocols for both uplink and downlink. Seamless roaming of clients was achieved, while the channel utilization efficiency was improved considerably. H. Xiaoxiao et al. [19] developed a transport layer protocol to move bits from expensive cellular data networks to relatively cheaper

[1] http://web.scalable-networks.com/content/qualnet.