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Distributed and adaptive resource management in Cloud-assisted Cognitive Radio Vehicular Networks with hard reliability guarantees

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ABSTRACT

In this contribution, we design and test the performance of a distributed and adaptive resource management controller, which allows the optimal exploitation of Cognitive Radio and soft-input/soft-output data fusion in Vehicular Access Networks. The ultimate goal is to allow energy and computing-limited car smartphones to utilize the available Vehicular-to-Infrastructure WiFi connections for performing traffic offloading towards local or remote Clouds by opportunistically acceding to a spectral-limited wireless backbone built up by multiple Roadside Units. For this purpose, we recast the afforded resource management problem into a suitable constrained stochastic Network Utility Maximization problem. Afterwards, we derive the optimal cognitive resource management controller, which dynamically allocates the access time-windows at the serving Roadside Units (i.e., the access points) together with the access rates and traffic flows at the served Vehicular Clients (i.e., the secondary users of the wireless backbone). Interestingly, the developed controller provides *hard* reliability guarantees to the Cloud Service Provider (i.e., the primary user of the wireless backbone) on a per-slot basis. Furthermore, it is also capable to self-acquire context information about the currently available bandwidth-energy resources, so as to quickly adapt to the mobility-induced abrupt changes of the state of the vehicular network, even in the presence of *fadings*, *imperfect* context information and *intermittent* Vehicular-to-Infrastructure connectivity. Finally, we develop a related access protocol, which supports a *fully distributed* and *scalable* implementation of the optimal controller.

1. Motivation and goals

In this paper, we focus on Cloud and Internet-assisted Vehicle-to-Infrastructure (V2I) communication for emerging non-safety applications, which require the Quality of Service (QoS) up/downloading of large amounts of data, such as, podcast subscriptions of audio/video programs, digital map downloading/updating, Web surfing, advertising applications and opportunistic vehicular-assisted content delivery applications. In fact, it is expected that these bandwidth-demanding applications will have a significant impact on the commercial success of Vehicular Cloud Computing (VCC) and will contribute to accelerate its implementation and deployment [1]. However, in order to continue to guarantee higher priority to the traffic flows generated in downlink by the Service Providers, hard upper bounds must be imposed on the tolerated instantaneous rate of packets collision among the backbone traffic (that is, the primary traffic) and the access traffic (that is, the secondary traffic). Several recent studies (see, for example, [2] and references therein) about the mobile computation offloading in real-life cloud-assisted scenarios point out that the usage of WiFi-based traffic offloading in place of 3G-assisted one may reduce the average energy consumption of current smartphones of about 55%. About the spectral crowding of current vehicular networks, the communication traffic flows typically generated by safety applications and routed in downlink over the available backbones are of burst-type. Hence, these flows present inter-arrival gaps of non-negligible time durations, which can be opportunistically exploited by VCs equipped with Cognitive Radio (CR) smartphones to accede to the serving RSUs through WiFi connections [3].

Therefore, motivated by the aforementioned considerations, in this paper we consider the V2I CR-based access scenario of Fig. 1, where multiple car smartphones equipped with heterogeneous cognitive capabilities and energy budgets play the role of secondary users and compete for acceding to the serving RSUs by opportunistically exploiting the time and frequency holes of the

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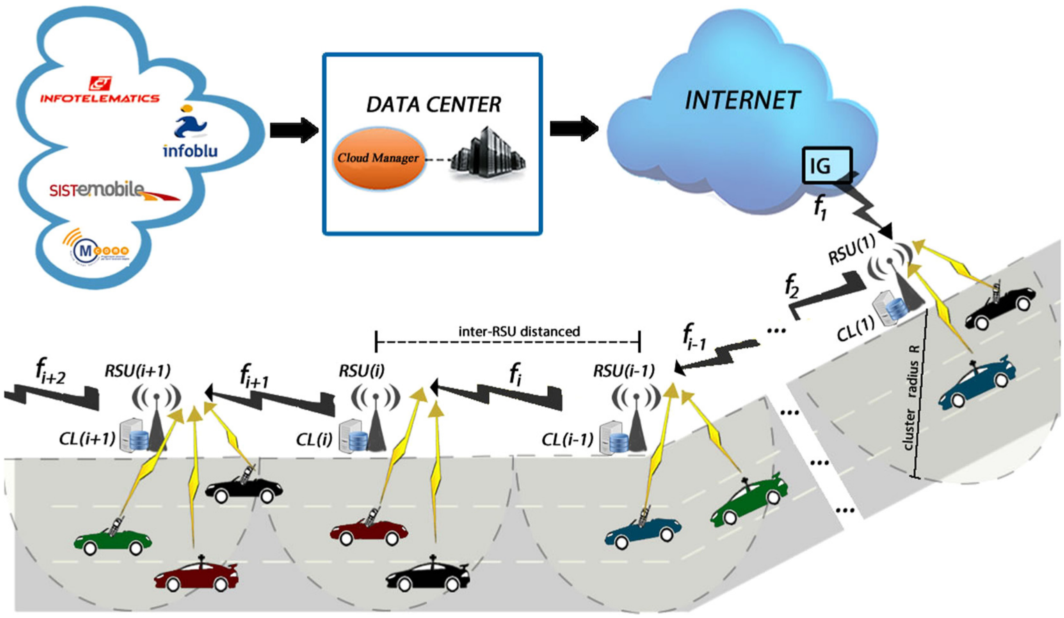

Fig. 1. The considered networked VCC infrastructure. The arrows refer to the downlink phase of each super-frame. RSU : Road Side Unit; CL : CloudLet; IG : Internet Gateway.

traffic flow generated by the Service Provider (that is, the primary user of the Internet backbone). The pursued twofold objective is the joint maximization of the aggregate access goodput of the overall network, and the average per-client access rates.

1.1. Technical contribution overview and main idea of the paper

With respect to the technical contribution of the work and the novelty of the idea, the target of the paper is to optimize the access throughput of the secondary user of the vehicular networks, while respecting the quality of service (QoS) requirements of the primary users, expressed in terms of maximum tolerated collision-rate with the secondary users. From this point of view, the paper propose a new optimized medium access control (MAC) protocol, able to maximize, under some assumptions detail below, the average aggregate throughput of the system. The proposed MAC protocol is new because of the following reasons: 1) it is a MAC Protocol able to manage two different classes of users, it is scalable, and from this point of view can be applied to any scenario of this form, not only the vehicular one we are here considering; 2) furthermore, unlike other approaches, we chose not to control just the collision probability among users, but the instantaneous collision rate. We are motivated from the consideration of the high time-varying nature of vehicular networks. In fact, more conventional approaches, even if they fulfill the collision probability constraints, may incur in quite long transients, where the instantaneous collision-rate is definitely too high, thus completely destroying the information; 3) our MAC strategy takes fully into account the energy, the parameters and the specific fading phenomena of the vehicular wireless channels in the optimization framework; 4) by introducing data-fusion techniques in our protocol, we allow secondary users to use the information broadcasted from the access point (AP) in order to optimize locally their queries, that is the requested throughput at the AP slot-by-slot, before the resource allocation decision is taken by the AP. This idea is somehow new, and couples the client throughput optimization with the MAC problem. Our approach is able to make it solvable, and computationally tractable with a very low computational cost; 5) finally, the proposed protocol is completely scalable, and can be used even in rougher situations where the signaling exchange is more limited, for example by removing the data fusion module or keeping the client optimization and the MAC optimization decoupled.

1.2. Related work and outline of the paper

Passing to consider the related work, very few papers [4–6] on the cognitive scheduling for the V2I access have been published so far. Specifically, Alcaraz et al. [4] assumes that the RSU knows the connection lifetime of each served VC in advance, so as to give higher priority to the clients with less data to upload and/or smallest remaining connection lifetime. This scheduling scheme, although pioneering in exploiting some peculiar features of the V2I networks, is not specifically compatible with the IEEE802.11x standards and neglects to consider the link quality aspect. The latter is, indeed, explicitly accounted for in [5,6], which develop optimized IEEE802.11e compliant access scheduling policies supporting QoS differentiation. However, neither fading-induced energy constraints nor context-aware cognitive approaches are considered by these contributions.

Among the rich set of papers affording the more general topic of the resource management in Cognitive Wireless Mesh Networks (*CWMNs*), the contributions in [7–12] pursue solving approaches which, as in our case, are inspired by the principle of the Network Utilization Maximization (*NUM*). Specifically, Bazerque and Giannakis [7] present a distributed scheduling and resource allocation scheme for OFDMA-based CWMNs, which aims at maximizing a (suitably) weighted linear combination of the client rates. Although the proposed scheme may represent a good starting framework for the resource management in multicarrier CWMNs, the burst nature of the Internet traffic and the related queue aspects are not considered in [7]. On the other hand, the solving approach of Urgaonkar and Neely [8] is based on the constrained stochastic optimization and queue control, and, indeed, it is the most similar to that pursued by our contribution. However, our work differentiates from [8] under the following main aspects. First, the application scenario considered in [8] is fading-free, so that neither energy constraints and data fusion nor the effects of imperfect context information are considered therein. Second, unlike our framework, Urgaonkar and Neely [8] assume that each mobile client is equipped with an infinite-capacity buffer.