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Data transmission plan adaptation complementing strategic time-network selection for connected vehicles

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ABSTRACT

Connected vehicles can nowadays be equipped with multiple network interfaces to access the Internet via a number of networks. To achieve an efficient transmission within this environment, a strategic time-network selection for connected vehicles has been developed, which plans ahead delay-tolerant transmissions. Under perfect prediction (knowledge) of the environment, the proposed strategic time-network selection approach is shown to outperform significantly leading state-of-the-art approaches which are based either on time selection or network selection only. Under realistic environments, however, the efficiency of planning-based approaches may be severely compromised since network presence and available capacities change rapidly and in an unforeseen manner (because of changing conditions due to the uncertainty in car movement, data transmission needs and network characteristics). To address this problem, a mechanism is proposed in this paper that determines the deviation from the anticipated conditions and modifies the transmission plan accordingly. Simulation results show that the proposed adaptation mechanisms help maintain the benefits of a strategic time-network selection planning under changing conditions.

1. Introduction

Nowadays, mobile nodes typically integrate different wireless network interfaces. An example environment of wireless networks is shown in Fig. 1, covering one mobile network (yellow) and three WiFi networks (blue, green, red) that are available for limited time spans during the trip. To improve connectivity performance, connected vehicles may use these networks in parallel to distribute their data traffic. Moreover, the connected vehicle use case provides an additional optimization potential, especially considering automated vehicles: Routes are usually known in advance and, thus, movement can be predicted accurately. As a result, a vehicle can predict future network availability and characteristics using the so-called connectivity maps, which use geographically mapped indicators to estimate the local transmission quality of available networks [1,2]. An exemplified prediction of network availability over time is visualized in Fig. 1 using colored bars. Furthermore, according to Sandvine [3], a major part of a mobile node's data traffic is delay-tolerant or heavy-tailed. Assuming networks and data traffic to be roughly known for a certain time horizon, we show in prior work [4] that a transmission planning can provide significant benefits. The transmission planning approach combines network selection [5] with a selection of the transmission time [6]. The approach plans ahead data transmission over multiple networks. In this paper, we present additional insights on the performance characteristics of this approach. However, the presented approach assumes perfect prediction of vehicle movement, network characteristics and data to transmit, as visualized in Fig. 2 left. Such accurate prediction might not always be available. In the real world, further mechanisms have to cope with prediction errors. Accordingly, we present three contributions in this paper:

(1) A strategic time-network selection approach that maximizes transmission efficiency using heterogeneous wireless networks due to transmission planning (Fig. 2 blue arrow "Plan").
(2) An investigation of the effects of erroneous prediction on the performance of transmission plan execution (Fig. 2 red arrow "Real World").

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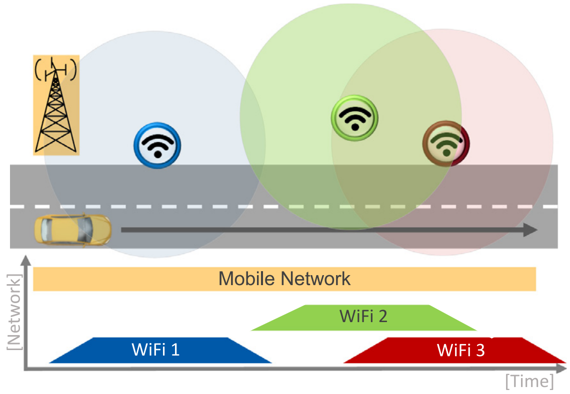

Fig. 1. Connected vehicle using heterogeneous wireless networks: example scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

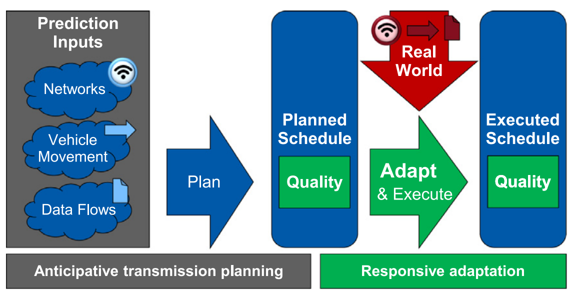

Fig. 2. System overview: prediction-based transmission planning complemented by adaptation for plan execution.

(3) A transmission plan adaptation that can mitigate a negative impact of erroneous prediction (Fig. 2 green arrow "Adapt & Execute").

In Section 2, we briefly outline our previous work on an anticipative data transmission planning assuming static conditions and perfect knowledge of the environment and compare it to an Opportunistic Network Selection (ONS) (no planning or prediction). We show its performance characteristics in different scenarios and compare it also to other state-of-the-art-based approaches. Furthermore, we introduce our prediction error models and show that the performance of the strategic time-network selection approach degrades severely in the presence of prediction errors, due to its inability to react to changing conditions. In contrast, the opportunistic approach ONS – although underperforming with respect to the transmission plan approach under static conditions and perfect knowledge – appears to deliver a constant performance as it does not rely on prediction. Its insensitivity to prediction errors provides the motivation for our proposed transmission plan adaptation mechanism, presented in Section 3, which complements the transmission planning. The benefit of each planned transmission is re-evaluated and the planned transmission is modified by invoking a constrained ONS taking into account the type and magnitude of condition changes (i.e., car movement, data flows or network characteristics); mechanisms detecting relevant condition changes are also introduced. In Section 4, we discuss the performance of our novel adaptation approach under various changing conditions, followed by a related work discussion in Section 5. It turns out that under small to moderate changes in the environment, our responsive adaptation approach can largely sustain the gain foreseen from anticipative transmission planning with strategic time-network selection.

2. Data transmission planning

The predictable movement of multi-homed mobile clients enables a transmission planning over networks and time. In our prior work [4,7], we demonstrate significant benefits of such a planning in comparison to state-of-the-art approaches. In this section, we summarize the approach, the evaluation metrics and results of this work and extend it with new insights. This constitutes the base for the adaptation approach proposed and evaluated in this paper.

2.1. Evaluation metrics and model of forces

To assess the efficiency of our strategic time-network selection approaches, we developed a performance rating function, that captures application QoS requirement satisfaction and monetary cost. We bisect the performance rating function into two components that are in effect in a mutually exclusive manner depending on whether data is allocated or not. We call the first component the attracting forces c_{attr}. It captures cost associated with data that is not allocated to a network, punishing the violation of a minimum throughput requirement and the amount on non-allocated data. The second component, referring to as the repelling forces c_{rep}, captures cost associated with data that is allocated to a network, punishing the violation of the QoS requirements of the data flows or monetary transmission cost. It covers components from network selection, like latency, jitter and also components from transmission time selection approaches, including deadline and the preferred start time of data transmissions, as visualized in Fig. 3.

Networks attract data for allocation in general through c_{attr}, creating attracting forces for each data flow according to its priority. In addition, the repelling forces push data away from networks and time slots that cannot satisfy the data flow's QoS requirements. The rating function in Eq. (1) adds the two mutually exclusive components for a given transmission plan p. Note that p^* is an alias for p, indicating that the given model component punishes the absence of a desired transmission in a plan.

$$c(p) = c_{attr}(p^*) + c_{rep}(p) \tag{1}$$

Minimizing the cost function results in a data allocation to the best matching networks at matching points in time over the complete planning time horizon. For the detailed model of the cost function, refer to [4,7]. It is summarized in Fig. 3.

As the absolute value of the cost in Eq. (1) strongly depends on the scenario, a Normalized Rating Score (NRS) is introduced to allow for a meaningful comparison of multiple scenarios. *NRS describes a transmission plan's achieved share of the absolute optimization potential of the given scenario.* A value of 0.8 means that a transmission plan uses 80% of the scenario's optimization potential. To define the optimization potential, we employ an upper and a lower cost bound. As a lower cost bound, we use the cost of an optimal transmission plan. As an upper cost bound, we use the average cost of valid random transmission plans. We assume this as a reasonable upper cost bound for rating because no transmission plan, which was created with intent, should perform worse than random. Higher values are still feasible.

2.2. Transmission planners

Transmission planners determine data allocation to networks and over time. We analyze three transmission planners from [4] in this paper and an additional one for transmission time selection. All of them use the same ratings for network selection and data flow prioritization to create comparability of their results. However, they differ in the way they handle the time dimension.

The first is a *Network Selection (NS)*. It is derived from state-of-the-art approaches and allocates data to the *currently* available