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Analytic Approaches for Obtaining the Communications Requirements of String Stable Platooning

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Abstract

Mobile radio networks promise to enable connected automated driving simultaneously with other automated applications, such as those from Industry 4.0. Stringent communications demands on networks are expected from these interconnected automated processes. Since it is anticipated that these appliances share network resources, the issue of shortage of radio resources quickly exacerbates with an increasing number of devices. The radio resource bottleneck exhibits itself as a performance degradation of the connected automated processes. For the case of connected automated driving, the consequences of this communications deterioration can be catastrophic, underscoring the importance of fulfilling their communications demands. From a network perspective, the efficient usage of the shared communications resources is likewise significant; the network aims at maximizing the number of connected users without compromising their operation.

Within connected automated driving, platooning is a relevant application given its benefits in safety, traffic and energy efficiency. These advantages only prevail if the platoon remains string-stable for short intervehicle distances. String stability in connected platooning is determined by distinctive interdependences among the control and communications parameters. While simulation-based studies have broadened the intuition on such interdependencies, their rigorous mathematical description has been missing.

The primary aim of this thesis is to formulate a mathematical framework that reveals the interdependences among the communications and control variables of platoons. From the proposed models, communications requirements of string-stable platoons can be obtained analytically in terms of the platoon dynamic properties. These properties are mostly dictated and stated in terms of the control loop parameters of its member vehicles. By studying the dynamic properties of the vehicle models under a well-defined performance metric, the proposed frameworks relate the control parameters with the communications variables.

Under centrally managed channel access schemes and negilible packet losses on the vehicular links due to line-of-sight transmissions, interference-free discrete-time periodic communications can be enforced. For this case, a frequency-domain model was developed for obtaining the periodic maximum allowed transmission intervals, the maximum allowed delay and their tradeoffs for enabling string-stable heterogeneous platoons. These results are further used as QoS constraints in the design of a LTE-V2X semi-persistent scheduler and validated via numerical simulation.

A generalization of the models for considering non-deterministic communications

intervals due to aperiodic transmissions and packet losses on the vehicular link was further developed. Relying on the theory of dissipative systems, an aperiodic maximum allowed transmission interval per vehicular link is found. For obtaining the upper bounds on the probability of packet losses that a string-stable platoon can tolerate, the system is modeled as a stochastic switching system. The resulting switching model incorporates not only the vehicular kinematics, but also additional properties such as the dynamics of the tracked signal of the preceding vehicle and packet loss probabilities on the considered vehicular communications link.

The generalized models explain how discrete-time communications introduces a communications-induced error into the control system on time intervals in-between receptions. This revelation motivated applying state estimation techniques to further relax the aperiodic maximum allowed transmission intervals and the upper bounds on the probability of packet losses per link of a string-stable platoon.

Results show that communications requirements of string-stable platoons strongly depend on the control loop parameters dictating the dynamic properties of the vehicles. The resulting upper bounds on packet loss probabilities and transmission intervals do not always fall into the stringent domain as commonly theorized, especially when state estimation techniques are employed on the follower cars. Consequently, the scalability problem in the network is alleviated by exploiting the vehicles' dynamic properties. Furthermore, the heterogeneity of vehicles induce different communications demands within platoon members, providing additional degrees of freedom for the radio resource allocation.

An implication of understanding communications-control interdependencies is encouraging the development of strategies in either control or communications to compensate deficiencies in their respective co-domain. Another ramification of the findings in this work is on establishing a new paradigm for communications engineers interconnecting heterogeneous automated processes: their distinct dynamic properties provide a type of diversity that is exploitable through radio resource management.

While the here derived methodologies explain the interdependencies between the co-domains of communications and control in connected platooning and the presented results apply only for this use-case, the present research and techniques may serve as incentive and tools for expanding the knowledge and obtaining communications requirements of other networked automated processes.

Kurzfassung

Mobilfunknetze bieten die Möglichkeit das vernetzte automatisierte Fahren gleichzeitig mit anderen automatisierten Anwendungen, wie z. B. der Industrie 4.0, zu realisieren. Diese vernetzten automatisierten Prozesse stellen hohe Kommunikationsanforderungen an die Netze. Da sich die Geräte die Netzwerkressourcen teilen sollen, verschärft sich das Problem der Knappheit an Funkressourcen mit zunehmender Geräteanzahl schnell. Der Engpass der Funkressourcen äußert sich in einer Leistungsverschlechterung der angeschlossenen automatisierten Prozesse. Im Falle des vernetzten automatisierten Fahrens können die Folgen dieser Kommunikationsverschlechterung katastrophal sein, was die außerordentliche Wichtigkeit betont, die Kommunikationsanforderungen zu erfüllen. Aus der Perspektive des Netzwerkes ist die effiziente Nutzung der gemeinsam genutzten Kommunikationsressourcen ebenfalls von Bedeutung; das Netzwerk zielt darauf ab, die Anzahl der angeschlossenen Nutzer zu maximieren, ohne deren Betrieb zu beeinträchtigen.

Im Rahmen des vernetzten automatisierten Fahrens ist das Konvoi-fahren aufgrund seiner Vorteile in Bezug auf Sicherheit, Verkehr und Energieeffizienz eine relevante Anwendung. Diese Vorteile sind jedoch nur dann gegeben, wenn der Konvoi bei kurzen Abständen zwischen den Fahrzeugen strangstabil bleibt. Die Strangstabilität beim vernetzten Konvoi wird durch ausgeprägte gegenseitige Abhängigkeiten zwischen den Steuerungs- und Kommunikationsparametern bestimmt. Während simulationsbasierte Studien die Intuition gegenüber solchen gegenseitigen Abhängigkeiten erweitert haben, fehlte bisher eine rigorose mathematische Beschreibung dieser gegenseitigen Abhängigkeiten.

Das primäre Ziel dieser Arbeit ist es, einen mathematischen Rahmen zu formulieren, der die Abhängigkeiten zwischen den Kommunikations- und Regelungsvariablen von Konvois aufzeigt. Aus den vorgeschlagenen Modellen lassen sich die Kommunikationsanforderungen von strangstabilen Konvois analytisch in Form der dynamischen Eigenschaften des Konvois ableiten. Diese Eigenschaften werden größtenteils durch die Regelkreisparameter der Mitgliedsfahrzeuge bestimmt und angegeben. Durch die Untersuchung der dynamischen Eigenschaften der Fahrzeugmodelle unter einer wohldefinierten Leistungsmetrik setzen die vorgeschlagenen Rahmenwerke die Regelungsparameter mit den Kommunikationsvariablen in Beziehung.

Unter zentral verwalteten Kanalzugangsverfahren und vernachlässigbaren Paketverlusten auf den Fahrzeugverbindungsstrecken aufgrund von Ausbreitung bei Sichtverbindungsübertragungen kann eine störungsfreie diskrete, periodische Kommunikation durchgesetzt werden. Für diesen Fall wurde ein Modell im Frequenzbereich entwickelt, um die maximal zulässigen periodischen Übertragungsintervalle, die maximal zulässige Verzögerung und ihr Ausgleich des Zielkonfliktes zu ermitteln,

um stabile heterogene Konvois zu ermöglichen. Diese Ergebnisse werden als QoS-Beschränkungen beim Entwurf eines semi-persistenten LTE-V2X-Schedulers verwendet und durch numerische Simulationen validiert.
Eine Verallgemeinerung der Modelle zur Berücksichtigung nicht-deterministischer Kommunikationsintervalle aufgrund von aperiodischen Übertragungen und Paketverlusten auf der Fahrzeugverbindungsstrecke wurde ebenfalls entwickelt. Auf der Grundlage der Theorie dissipativer Systeme wird ein aperiodisches maximal zulässiges Übertragungsintervall pro Fahrzeugverbindung ermittelt. Um die Obergrenzen für die Wahrscheinlichkeit von Paketverlusten zu ermitteln, die ein strangstabiler Platoon tolerieren kann, wird das System als ein stochastisches Vermittlungssystem modelliert. Das resultierende Vermittlungsmodell berücksichtigt nicht nur die Fahrzeugkinematik, sondern auch zusätzliche Eigenschaften, wie die Dynamik des verfolgten Signals des vorausfahrenden Fahrzeugs und Paketverlustwahrscheinlichkeiten auf der betrachteten Fahrzeugkommunikationsverbindung.
Die verallgemeinerten Modelle erklären, wie die zeitdiskrete Kommunikation einen kommunikationsinduzierten Fehler in das Kontrollsystem in den Zeitintervallen zwischen den Empfängen einführt. Diese Erkenntnis motiviert die Anwendung von Zustandsschätzungsmethoden, um die aperiodischen maximal erlaubten Übertragungsintervalle und die oberen Grenzen der Wahrscheinlichkeit von Paketverlusten pro Verbindung eines Strangstabilen Platoon weiter zu lockern.
Die Ergebnisse zeigen, dass die Kommunikationsanforderungen eines strangstabilen Konvois stark von den Parametern des Regelkreises abhängen, die die dynamischen Eigenschaften der Fahrzeuge bestimmen. Die sich daraus ergebenden Obergrenzen für Paketverlustwahrscheinlichkeiten und Übertragungsintervalle fallen nicht immer, wie allgemein angenommen in den strengen Bereich von Kommunikationsanforderungen, insbesondere wenn Zustandsschätzverfahren auf den Folgefahrzeugen eingesetzt werden. Folglich wird das Problem der Skalierbarkeit des Netzes durch Ausnutzung der dynamischen Eigenschaften der Fahrzeuge abgemildert. Darüber hinaus führt die Heterogenität der Fahrzeuge zu unterschiedlichen Kommunikationsanforderungen innerhalb der Konvoimitglieder, was zusätzliche Freiheitsgrade für die Zuteilung von Funkressourcen bietet.
Eine Folge des Verständnisses der Abhängigkeiten zwischen Kommunikation und Regelung ist die Förderung der Entwicklung von Strategien entweder in der Regelung oder in der Kommunikation, um Unzulänglichkeiten in der jeweiligen Co-Domäne zu kompensieren. Eine weitere Auswirkung der Ergebnisse dieser Arbeit ist die Einführung eines neuen Paradigmas für Kommunikationsingenieure, die heterogene automatisierte Prozesse miteinander verbinden: Die unterschiedlichen dynamischen Eigenschaften der Prozesse bieten eine Art der Diversität, die durch das Management von Funkressourcen genutzt werden kann.

Während die hier abgeleiteten Methoden die gegenseitigen Abhängigkeiten zwischen den Co-Domänen der Kommunikation und der Regelung im vernetzten Konvoi erklären und die vorgestellten Ergebnisse nur für diesen Anwendungsfall gelten, können die vorliegenden Forschungen und Techniken als Anregung für die Erweiterung des Wissens und die Ermittlung der Kommunikationsanforderungen anderer vernetzter automatisierter Prozesse dienen.

Dedication

"To my life partner Anja and my son Benjamin, which although research is my passion, they remind me every moment that they are my reason to be."

"To my parents and their self-sacrifizing efforts while raising us. You did everything right."

Arturo

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Contents

1 Introduction

Connected and automated vehicles anticipate advantages on numerous aspects in our society. The predicted benefits range from the most obvious such as increments in traffic efficiency, reduction of accidents, shortening of commuting time and decrease in energy usage along with pollution, to more subtle improvements including increase of productivity, comfort upgrades, higher accessibility to mobility and creation of new markets. The rapid development of automated vehicles in the last years have driven industrial experts to suggest that their widespread adoption will take off by 2030 [PPW19]. While this statement allows speculation, the role of communications in connected autonomous vehicles has consolidated unequivocally. Vehicle-to-Vehicle (V2V) communications for cooperative automated driving are not only advantageous but sometimes indispensable for enabling certain scenarios. They are considered essential for creating a full ecosystem of intelligent transportation systems [Cat17]. Through V2V communications, automated vehicles and other traffic actors can interact explicitly and partake in joint decision making. Moreover, communications can alleviate sensor limitations, enhance perception through cooperative awareness and reduce the amount of sensors otherwise required without them.

Modern mobile and wireless technologies have reached performance levels comparable to their wired counterparts. As their deployment expand and capabilities grow, they have began establishing themselves as enablers for automated processes in industry and transportation. The Long-Term Evolution (LTE) standard, for example, defines a vehicle-to-vehicle specific technology as a subset of LTE. The progression towards Fifth-Generation of Mobile Radio Networks (5G) pushes the definition of new standards and conception of technologies specific for cooperative automated vehicles. The capabilities that 5G assures opens new possibilities and leverages performance in use-cases involving connected automated driving. One of these use cases is automated convoy driving or more commonly referred as automated platooning.

Longitudinal platooning consist of vehicles driving in a line or string formation following closely their predecessors at a determined cruising speed. As described below, driving in a platoon exhibits several advantages. Automated longitudinal platooning, or platooning for short, is also seen as a milestone use-case in transport automation on which more complex situations can be build upon.

1.1 Vehicle Platooning

Research on vehicular platooning took off in 1986 with the establishment of the California PATH partnership. Within PATH, platooning was initially devised as an economically feasible solution to solve the growing traffic congestion problem in California at the time [Shl]. By 1994, the first demonstration of a platoon consisting of four vehicles equipped with throttle and brake actuators, radar, wireless LAN and the required control computers and software has been successfully deployed in San Diego [Shl]. Since then, numerous research groups have studied platooning from different facets, including traffic efficiency (e.g. [vAvDV06], [SLF+00], [LPY+17], [SSL12]) fuel efficiency (e.g. [BF00], [LSLK20]), aerodynamic performance (e.g.[ZSFB95]), safety (e.g [Axe17]), controller design (e.g. [PSvdWN14], [vNVSvdW17]), network topologies (e.g. [SH99]) and more recently, on communications aspects (e.g. [SVR+00], [SBJ+15], [NVC+18], [Önc14]).

1.1.1 Motivation

The main motivation for vehicular platooning has expanded since its conception, mainly due to the benefits its brings in traffic and fuel efficiency, safety and comfort. In [vAvDV06], it was shown that platooning has positive effects on traffic throughput in highways. For the scenario when a highway narrows due to a lane drop, traffic shockwaves before and after lane drops decreased when platooning was applied. Moreover, the throughput in normal driving situations was improved when the market penetration rate of platoon-capable vehicles exceeded 60%.

Similar conclusions relating market penetration rates and traffic capacity improvements of platooning are reached by the authors of [SSL12]. Based on real drivers data, they study the effects of different market penetration rates of sensor-only and sensor-plus-communications platooning on freeway capacity. Remarkably, sensor-only platooning does not result in net increments of traffic capacity. In contrast, communications-enhanced platooning through sensors-plus-V2V communications results in increments of above 10% and 50% for market penetration rates of 30% and 60%, respectively. Dramatic traffic capacity increments of above 80% are seen for a 100% market penetration rate of communications-enhanced cooperative platooning. The results in [SSL12] emphazise the importance of augmenting platooning with V2V communications for maximizing traffic capacity.

Platooning can alleviate traffic bottlenecks in intersections as well. In [LPY+17], the authors conclude that platooning can increase bottleneck capacities at urban intersections by a factor of two to three. The same conclusion was achieved in [SLF+00], where the authors also determined that platooning can considerably improve the traffic efficiency at street crossings. The qualitative throughput improvements they reach through simulations are consistent with those reported in [LPY+17].

The reduction in fuel consumption in platooning results from the minimization of the aerodynamic drag in the follower vehicles. In [ZSFB95], experiments conducted in wind tunnels for passenger cars in a platoon configuration are reported. The results show that the average fuel savings for platoons of 4 vehicles traveling at 110 km/hr range between 6% to 20% for intervehicle distances remaining under 10 meters. In [BF00], results from outdoor platooning experiments performed on a pair of heavy trucks traveling at 80 km/hr are reported. The fuel savings for intervehicle distances between 7 to 16 meters range within 15% to 8%, respectively. Higher fuel savings for longer platoons are forseen by the authors.
These expectations are confirmed in [LSLK20], where studies on the impact in fuel savings for different market penetration rates of communications-enhanced platooning are disclosed. The authors report a maximum of 20% fuel reduction on freeway merge bottlenecks when compared to human drivers. Furthermore, it is shown that at 100% market penetration rate, communications-augmented vehicles engaged in platooning consume 50% less fuel than their sensor-only counterpart. Together with the outcomes stated in [SSL12], these results underscore the advantage of vehicular control systems enhanced with V2V communications.

A less studied but relevant benefit in platooning is comfort. Under full automation, drivers can rest during long commutes or while extended driving periods are covered. This aspect becomes more relevant for freight drivers involved in supply chain transportation involving long routes.

Platooning might also be seen as cornerstone for other more complex cooperative automated driving use-cases [CMAB17]. Its well-studied properties can be extended to aid in the analysis and design of such scenarios in the near future. One example could be lane merging in which within a platoon, the gap between vehicles is regulated for allowing the merge to happen.

From a theoretic perspective, studying platooning is interesting due to the properties it exhibits. By design, the control systems of the vehicles within a platoon are dynamically coupled [Dar97]. This means that the action of one vehicle will propagate towards its followers. Studying the fundamental properties of dynamic coupled systems and the role of information exchange through communications may aid in narrowing the gap between communications and control theories. Moreover, by studying the communications-control interactions in platooning, the obtained insights can be extended to other transportation and automation scenarios e.g. formation control.

1.1.2 Technical Background and Related Work

Automated platooning relies on longitudinal control systems that can attain short intervehicle distances in a safe manner. Automated Cruise-Control (ACC) and its communications-enhanced version, Cooperative Automated Cruise-Control (CACC), have become the longitudinal control system of choice and a synonym of platooning. (C)ACC is an extension of the well-established Cruise Control (CC) [Raj12]. Equipped with a distance sensor, i.e. a radar or lidar, ACC essentially changes the target speed of the CC by comparing the current intervehicle distance with a desired reference.

A central component in platooning is the control strategy employed in each of the individual vehicles. The (C)ACC controller within each vehicle attempts to reach a reference intervehicle distance between a vehicle and its predecessor. A commonly selected controller is the Proportional-Derivative (PD) controller. This controller strategy has been used in [NVP+10], [PSvN+11], [Önc14] to name a few, and has been shown to produce satisfactory results in (C)ACC [Raj12].
Alternative control strategies have also been proposed. In [PvdWN14], an $\mathcal{H}_\infty$ controller is designed for a CACC system while considering a simplistic communications model and assuming its parameters constant and known. In [SSV+15], a consensus-based approach that does not require apriori knowledge on the topology nor that vehicles be equipped with radar is presented. Strategies based on non-linear approaches have been considered for platooning as well. In [Raj12], a sliding mode controller is derived. The approach has become recurrent in simulation-supported research such as [SVR+00] and [SSV+15] due to its implementation in open-source simulators. Clearly, research in control strategies for platooning has been an active topic since its origins.

While it seems there are several choices for a platooning control strategy, the strategy of choice will strongly depend on the spacing policy between vehicles and the platooning performance goals.
Early analysis on the vehicle following problem proved that platooning is a dynamic coupled system [Dar97]. Perturbations occurring at the platoon lead, such as braking and accelerating, propagate down the vehicle string. These propagating perturbations exhibit themselves as intervehicle distance errors which consequently reflect in an amplification of the control and kinematic variables. Depending on the system properties, these perturbations may increase in amplitude or energy as they disseminate towards the end of the platoon. This undesired feature is referred as string instability [Dar97] and will be formalized and thoroughly studied in Chapter 3.

The recognition of string instability and its formal description in platooning lead to extensive research in the design of longitudinal control strategies which were additionally string stable. In [SHCI94], spacing policies between vehicle pairs and their consequences on string stability were studied. It was proven that a constant-distance spacing policy between vehicle pairs requires communicating the control information of the immediate preceding vehicle and the platoon leader to all platoon members. A disadvantage of this resulting network topology is that, for long platoons, communications between the leader and vehicles near the platoon end may become unreliable.

Another studied spacing policy in [SHCI94] is the constant-time spacing policy. As its name suggests, this policy targets a constant headway time between all vehicle pairs. It is a scalable alternative to the constant-distant spacing policy since it does not require disseminating the leader information to all platoon members. Under the constant-time spacing policy, string stable platoons with vehicles pairs driving with short headway times require communications from the immediate predecessor only. Moreover, for relatively large headway times or high controller gains, the system can rely on sensor-only information.

The constant (headway) time spacing policy is favored in this work for two main reasons; firstly under commercial wireless technologies where reliability and availability in connectivity cannot be yet guaranteed, a sensor-only backup serves as a redundant system for safety reasons. Secondly, predecessor-only communication leads to scalable, high-density platoons that can communicate in a vehicle-to-vehicle manner without explicitly requiring a network infrastructure[1] or large ad-hoc coverage distances likely affected by the wireless channel characteristics. Lastly, the CACC system design is simplified under the predecessor-only vehicular network configuration [SHCI94].

For the preferred constant headway time spacing policy, the PD controller provides good performance with excellent tractability. While other control strategies may result in better performance, in this work the PD controller is the control strategy of choice. The reason is threefold: Firstly, the PD controller has been shown to produce satisfactory results in (C)ACC [Raj12]. Secondly, the PD controller has been deployed in experimental scenarios and proven effective and reliable (see [NVP+10] and [PSvN+11]). Lastly, it is a tractable controller model which facilitates focusing on achieving one of the main objectives in this work; the derivation of the communications requirements in platooning.

Certainly, the results presented here, valid for the chosen control strategy, shall provide insights for analyzing the communications requirements in platooning with more complex control schemes.

[1] Although not a hard requirement, platooning may benefit from a mobile network infrastructure, as pointed out in Section 4.5

1.2 Communications Aspects in CACC Platooning

Maximizing the platooning benefits of traffic and fuel efficiency relies on accomplishing short headway times safely. As the analysis in Section 3.4 will show, platooning without communications cannot reach short headway times in a string-stable manner. This gives rise to the need for cooperative adaptive cruise control. By exchanging the control information in CACC, a follower vehicle can anticipate the actions of its predecessor before detecting them via radar. This enables achieving arbitrary short headway times in CACC platooning.

As mobile networks and wireless communications become pervasive and more capable, technologies such as LTE, 5G and 802.11p emerge as candidates for enabling CACC platooning. Nevertheless, wireless communications are far from ideal. Typical digital communications effects such as link latency, packet dropouts, link outages, limits on the transmission rates as well as the sampling effects of the transmitted signal will certainly affect the CACC performance. Moreover, with the rise of paradigms like the internet of things and the tactile internet [Fet14], modern communications technologies aim at serving a plethora of use-cases and scenarios within a limited radio spectrum. For these reasons it becomes paramount for a network to know the communications requirements of applications such as CACC platooning, not just for fulfilling these demands, but also for making efficient use of its radio resources and consequently serve more users simultaneously. Moreover, due to the dynamic nature of control systems such as CACC, the demands that these systems put on the communications technologies are as well dynamic. Knowing the communications requirements and how they depend on the dynamic parameters of control loops opens a door for developing control-aware, opportunistic channel access methods and Radio-Resource Allocation (RRA) schemes.

Other researchers have as well identified the need for obtaining and guaranteeing the communications requirements in CACC platooning. Few of them have identified the opportunity of studying the interdependencies of communications and control, e.g. [DKSC19]. Next section summarizes the state of the art on the communications aspects in CACC platooning.

1.2.1 Previous Work

Most existing work studying the communications aspects of CACC platooning assume either a fixed transmission rate dictated by a communications technology or a worst-case number. More seldom are investigations involving packet loss effects. Moreover, the effects of the communications on the platoon performance are usually studied through numerical simulations only, with few exceptions. While numerical simulations may provide insights on the behavior of the systems in question, their results are only valid for the set of parameters selected for the experiments. The clear drawback is that from certain obtained results it may not be possible to derive conclusions for the general case. In other words, simulations are no replacement for a thoroughly mathematical analysis, rather complementary.

Based on the control strategy from [Raj12], the work presented in [CMAB17] considers the architecture of leader-plus-predecessor with transmissions to all platoon members. The research focus lies on studying the feasibility of spatial reuse of radio resources by other vehicles and other platoons. The communications requirements are not derived; instead the transmission periods per vehicle are assumed fixed from the set of 10, 50 and 100 ms.

In [SVR+00], the control architecture from [Raj12] based on constant distance spacing policy is again assumed and further modified by the authors, hence proposing an alternative CACC algorithm. For the classical and the alternative CACC control structures, the communications effects on the platoon performance in terms of string stability, crash ratio and achieved minimum target distance are studied via detailed network-plus-traffic simulations. By interpreting their results, the transmission intervals required to achieve a defined performance are inferred from a set dictated by the communications technology assumed.

In [SBJ+15], the authors propose communications strategies based on the vehicle arrangement within the platoon and compare them with standarized protocols. The control loop architecture is again that one introduced in [Raj12]. The proposed communications strategies are synchronized communications slots with and without transmission power adaptation. The assumption is that all vehicles know their relative distance towards their followers as well as their relative position in the platoon. Using the relative distance towards their follower, the transmission power of a transmitting vehicle is adapted in an attempt to minimize interference to other vehicles. The channel access scheme proposed follows a sequential approach triggered by the platoon leader and based on the relative order of the vehicles within the platoon. Numerical and experimental evaluations are performed assuming a fixed transmission period of 100 ms for certain communications strategies, whereas other communications strategies use a dynamic rate. Nevertheless, the rate is determined not by the control system parameters, but solely on the communications network's state. The authors conclude that application-aware dynamic transmissions shall benefit cooperative automated driving applications such as platooning. This claim is supported by the present thesis.

The work presented in [SDL15] attempts exploiting the kinematic properties within

CACC platooning by proposing a communications scheme based on jerk, i.e. the time-derivative of the acceleration. The control architecture is again that from [Raj12]. The transmission instants between vehicles are determined when a parametric equation, function of the jerk, exceeds a threshold. The communications-triggering parametric equation proposed is not derived, is rather justified with extensive numerical simulations employing the software framework described in [SJB+14].
While the approach of exploiting the dynamic properties of CACC for communications in [SDL15] is aligned with the main Thesis of this work, no formal analysis regarding the relationship between the control and communications is presented. The authors conclude that a theoretical link between transmission intervals and the vehicle dynamics will help designing optimal networking protocols. This dissertation contributes to finding that link, if not in full, substantially.

A more formal analysis on the communications requirements of CACC platooning is presented in [Önc14]. The control strategy chosen there follows the one from [NVP+10] involving a PD controller and a constant time spacing policy. For the analysis regarding the effects of transmission intervals and transmission delays on CACC, the author casts the string-stable platooning problem into the Networked-Control Systems (NCS) framework from [HTvdWN10].
A shortcoming from [Önc14] is that the string stability condition is not enforced for all vehicle pairs. Instead, string stability is defined as the no amplification of the last vehicle's states with respect to the states of the platoon leader, assuming the leader is affected by a perturbation. As it will be explained in Chapter 3, this is a weaker string stability condition than when all vehicle pairs must enforce the no amplification of their states with respect to those of their immediate predecessor. Expressly, this *weak* condition implies that a platoon will be labeled string stable as long as the last vehicle spends less energy than its leader, allowing thus for relative amplifications on the states of vehicles located in-between the platoon extremes. This behavior is in general undesired since it contradicts the goal of platooning in terms of safety, comfort and traffic as well as fuel efficiency.
Under this weaker constraint, the author obtains an upper-bound on the interval which the platoon as a whole requires to access the communications network. The reason why this bound represents the bound for the whole platoon and not per vehicle pair is a direct consequence of considering the weaker string stability condition. While [Önc14] lays important foundations on which this dissertation partially develops on (see Chapter 5), its results cannot be generalized to heterogeneous platoons. Furthermore, these results cannot be used as communications requirements per vehicle pair serving as guidelines for control-aware, efficient radio resource allocation. In a heterogeneous platoon, distinct vehicle pairs will exhibit different upper-bounds

on the communications intervals.
From a network perspective, the heterogeneity property provides additional degrees of freedom for radio resource allocation. Similar to the concept of multi-user diversity [Mol11], heterogeneity in the modules of a NCS imposes diverse demands on the communications requirements. Such knowledge can be efficiently exploited for the design of efficient radio resource allocation algorithms while guaranteeing the performance constraints (see Chapter 4, Section 4.5). Hence, heterogeneity within platooning provides an application-level diversity that may be exploited by the radio network.
From a platooning perspective, the weaker string stability condition followed in [Önc14] does not guarantee the string stability metric for all vehicle pairs.
This dissertation tackles both network and platooning issues left open in [Önc14] by extending the theory presented there and consequently obtaining the upper-bound on the communications interval per string stable vehicle pair.

How string stability is affected by packet losses occurring on the vehicle-to-vehicle link is studied through numerical simulations in [LvK+11]. The authors consider the constant-time spacing policy with PD controller introduced in [NVP+10] as control strategy. By coupling a traffic, network and CACC simulators, numerical evaluations of the communications effects on the string stability of CACC were performed. By interpreting their results, it follows that for a given headway time, an increase in either the transmission period and/or Packet Delivery Rate (PDR) between vehicles makes the CACC system more susceptible towards string instability. Their results also show that for a fixed transmission period and PDR, increasing the headway time reduces the chances of CACC becoming string unstable.

With the goal of reducing the negative effects that packet drops on the vehicular link exert on CACC, authors in [vNVSvdW17] exploit a different control strategy, namely a Model-Predictive Control (MPC) implemented at each CACC-enabled vehicle. A MPC controller determines the control signal sequence for a given discrete-time horizon by solving a constrained optimization problem. The approach in [vNVSvdW17] consists of sending the computations obtained for the entire signal horizon and storing them at the receiving vehicle at every transmission period. In case that packet drops occur in the link, samples from the previously saved sequence can be employed while communications are restored. Through simulations, the authors show that the scheme provides robustness against packet losses when CACC is assessed through the string stability constraint. The costs of this robustness in terms of additional required bandwidth and processing power is not discussed.

An analytic approach to study the effects on packet losses in the vehicle following model is presented in [SS01]. Similar to the theory adopted in Chapter 5 for obtaining the bounds on the PDR of string stable CACC vehicle pairs, [SS01] models the effects of packet losses in the vehicle control loop as a Markovian Jump Linear System (MJLS). While in this dissertation the goal is to obtain the packet loss bounds under the string stability constraint for a given control strategy, in [SS01] the focus lies on finding a controller that is internally stable under an assumed given packet loss rate. If such controller is found, string stability is then assessed.

Tackling the communications aspects in platooning is not a domain exclusive for scholars. Standardization bodies have as well targeted defining the communications requirements of vehicle platooning. The Third Generation Partnership Programme (3GPP)[2] has defined the required transmission periods and the reliability requirements for platooning in what it seems a rather arbitrary manner. The technical specification [3GP19] prescribe transmission intervals of 33.33 and 20 milliseconds, depending on a relative degree of automation. The maximum end-to-end latency ranges between 10 and 25 milliseconds, also fixed according to the *automation level*. Reliability requirements, defined in terms of the probability of packets arriving within a latency budget, *must be sufficient* and reference values of 90% and 99.99% are given for the lowest and highest degree of automation, respectively.

The subjective definition of the communications requirements for platooning in [3GP19] is deficient in many aspects; firstly operating a platoon under these requirements may either result in a poor or dangerous performance or in an overprovisioning of radio resources by the network. Secondly, the communications requirements are defined as fixed and oversee the dynamic demands of CACC on communications. If the headway time within a platoon is modified due to e.g. a change in cruising speed, the communications requirements change as well. These dynamic properties, which allows for opportunistic, control-aware radio resource allocation are entirely ignored. The same issue occurs with the heterogeneous properties of CACC; the diversity on the communications demands resulting from different vehicle pairs on heterogeneous platoons is disregarded as well.
Lastly, because several control strategies exists, communications requirements among different control architectures will differ. Advanced signal processing and estimation techniques, for example, may relax the demands of CACC on communications (see Chapter 6). Overall the definition of the communications requirements for platooning by 3GPP is done agnostic to the CACC dynamic properties. This has detrimental effects on platooning and on the efficiency of the network operation.

[2] 3GPP is a global consortium of standardization organizations developing protocols for mobile telecommunications including LTE and 5G.

1.3 Identified Shortcomings and Research Objectives

The overview on the related work in previous section uncovers several open problems and shortcomings in current research regarding the communications aspects of cooperative platooning. Concretely, the identified shortcomings are:

- Within the research community and industrial organizations, no analytical methodology to obtain the communications requirements of for all heterogeneous, string-stable vehicle pairs within a platoon exists. The current approaches are either incomplete, inexact (i.e. based solely on numerical simulations), conservative or control-agnostic.

- The communications requirements of string-stable CACC platooning in terms of the control loop dynamic properties have not been fully understood. Numerical simulations have shown trends on the interplay between the control and communications variables, but a mathematical description of these relationships have been non-existent or incomplete, until now.

- Telecommunications communities, who strive in developing methods for scalable and efficient usage of radio resources, ignore to a large extend the degrees of freedom which heterogeneous dynamic system exhibit on their communications requirements. Hence, methodologies that take advantage of this knowledge are countable. Understanding the communications-control interactions and interdependencies shall lead to methodologies for scalable, control-aware and efficient usage of network resources.

- Methodologies for relaxing the communications demands that NCS exert on a wireless network are scarce. This issue exacerbates when the networking technology is a shared, multipurpose network such as LTE, 5G or WiFi.

Consequently, the following research objectives have been defined in this work.

1. Derive analytic methodologies that yield the communications requirements of the string-stable heterogeneous vehicle pairs within CACC platooning in terms of its control-loop dynamic properties.

2. Determine mathematical interactions between the control and communications parameters in CACC, as well as their trade-offs under the string stability performance metric.

3. By applying the results from the obtained methodologies, design efficient and control-aware radio resource allocation algorithms e.g. channel access

schemes, for contemporary wireless technologies that enable string-stable CACC platoons.

4. Investigate and propose strategies to minimize the communications demands that CACC imposes on the network technology without compromising the platoon's performance.

These objectives are accomplished through the following contributions organized within the Thesis outline.

1.4 Thesis Outline and Main Contributions

Including this introduction, this Thesis consists of seven chapters. Their content and the contributions are as follows.

Chapter 2

This chapter introduces the control system models of ACC and CACC platooning used throughout this work. Communications in CACC are assumed ideal in this Chapter to keep the focus on the control loop description.

The platoon system models result from solving the vehicle following problem. Its solution consist of finding a control strategy that can keep a specified distance between two consecutive vehicles. This intervehicle distance is given by the spacing policy, whose parameters play an important role on the platoon performance.

Following the constant (headway) time spacing policy, the control laws resulting in Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) are obtained from the vehicle dynamic model and its error space. The (C)ACC system models are given in both, frequency-domain and state-space representations. It is first obtained per heterogeneous vehicle pair and then combined to obtain the dynamic model for the entire platoon. The platoon state-space representation results in a cascaded control architecture with coupled states between consecutive vehicle pairs.

The contribution in this chapter lies in the extension of the frequency domain and state-space models of homogeneous platoons to the more general heterogeneous case. The resulting heterogeneous model per vehicle pair is then used to extend the lumped system model from [Önc14] for obtaining the the dynamic model of a heterogeneous platoon of finite size.

Both frequency and state-space heterogeneous (C)ACC models serve as foundations to obtain the communications requirements of string stable CACC platoons and study the relevant implications that heterogeneity has on them.

Chapter 3

String stability translates into traffic and fuel efficiency as well as into safe and comfortable operation of platoons. This chapter formalizes the concept of string stability as performance metric for (C)ACC in both time and frequency domains.

An important contribution in this Chapter is the derivation of the string stability condition between any two vehicle pairs as a dissipation inequality. This condition is referred as strong string stability. It is not only a desired property in all platoons but a necessity for obtaining the communications requirements per vehicle pair. Its derivation is done in the time-domain and obtained when perfect communications are assumed. While idealistic, the outcome serves as foundation for obtaining the strong string stability condition of CACC under realistic communications effects in Chapter 5. The derivation is achieved through Theorem 3.11 which is validated via computations. The numerical evaluations verify consistency with the hypotheses and with its frequency-domain counterpart presented in [NVP+10].

Through analysis, the fundamental limits of string stable ACC and CACC in terms of headway times are obtained as functions of the control loop parameters. The results describe the interaction among control loop variables when ideal communications are assumed. Under this hypothetical assumption, the analysis contributes in describing how heterogeneous plants, controller gains and minimum headway time under the string stability constraint relate to each other.

An additional contribution is showing that, for the ACC case, attempting to reduce the bound on the headway time solely by increasing the controller gains may lead to internal, control-loop instability. This conclusion reaffirms the need of communications for string-stable platooning under the selected the control architecture.

Finally, an alternative deduction on the mechanisms making CACC string stable when its ACC equivalent is not, is given at the end of the chapter. This explanation aids in understanding how communications may affect string stability in CACC.

The results in this Chapter serve as a baseline for those that follow, where communications effects are studied and their requirements in terms of transmission intervals, latency and packet dropouts are derived. These results also provide the preliminary insights for a CACC communications-control co-design.

Chapter 4

In this chapter, under the reasonable assumptions of periodic transmissions and no packet losses between vehicles, i.e. due to a line-of-sight vehicular channel, a frequency-domain model of a strong string stable CACC with imperfect communications is proposed. These assumptions lead to a tractable, Linear Time-Invariant (LTI) model where the digital communications effects such as sampling, transmission delay, and signal reconstruction at the receiver vehicle can be considered. The

obtained LTI model for strong string stable CACC endorses an analytic approach for finding the bounds of the transmission intervals and transmission delays per vehicular link. In fact, as it will be shown in this Chapter, there exist a trade-off between the two. The limits of this tradeoffs correspond to the Maximum-Allowed Transmission Interval (MATI) and Maximum-Allowed (Transmission) Delay (MAD). Hence, a main contribution in this Chapter is the analytical methodology for obtaining the communications requirements of strong string stable CACC, under the assumption of periodic communications and negligible packet losses in the communications link. The results obtained by applying this methodology are validated through time and frequency domain simulations.
A further contribution of this chapter is a throughout analysis of the influence of the control loop parameters in the communications requirements. Results in Section 4.4 convey how the communication requirements of strong string stable CACC are related to dynamic properties and parameters of its control loop.
As a last contribution in this Chapter and oriented towards practicality, Section 4.5 presents an efficient LTE for vehicle-to-vehicle communications (LTE-V2V) scheme designed to fulfill the communications requirements of heterogeneous, strong string stable CACC platoons. The scheme includes a Semi-Persistent Scheduling (SPS) scheme whose goal is to guarantee the obtained communications requirements of CACC with the minimum amount of required subchannels. Its design enforces periodic communications, assumes the practical half-duplex constraint of the LTE sidelink and other LTE-V2V standard configurations.
The design of the scheduler follows by deriving the mathematical conditions of conflict-free periodic and heterogeneous allocations, as described by Theorem 4.1.

Chapter 5

While the methodology from Chapter 4 proved quite effective, it relies on periodic updates between vehicle pairs. This chapter generalizes the communications model of Chapter 4 by considering non-deterministic update instants between any two consecutive vehicles. Such characteristic arises when aperiodic transmission intervals and packet losses on the vehicular link are assumed. The contributions within chapter are as follows:
Firstly, based on the work from [Önc14] and by applying the network-wide analysis from [NT04] adapted to the single-link case, a string stability condition for all vehicle pairs, i.e. strong string stability, under imperfect communications effects is proposed as a dissipation inequality. The obtained expression allows to compute the aperiodic maximum allowed transmission interval *per link* that fulfills strong string stability. While this approach yields more conservative results that the methodology from Chapter 4, the obtained bounds on the communications intervals between

consecutive vehicles are valid when updates occur at non-deterministic instants. Thus, a communications technology supporting strong string stable CACC is no longer restricted to periodic transmissions.

Secondly, in order to find the packet loss rates bounds that can guarantee strong string stability in heterogeneous CACC, the system with non-deterministic communications is modeled as an stochastic switching system. Conceptually, CACC switches between a subsystem with perfect communications at update instants and a subsystem where an error in the received update due to communications intermittency exists. The stochastic switching rates are given by the update rates, which themselves are dictated by the composition of transmission intervals and packet loss rates, and by the changes in tracked signal of the preceding vehicle.

Thirdly, trade-offs between packet loss rate tolerances, average transmission intervals and tracked signal properties are shown.

Lastly, the obtained results from this model are compared to results generated by casting the heterogeneous CACC with imperfect communications into the non-linear framework of [TN08]. The comparison shows that the packet loss rates obtained from the framework in [TN08] are somewhat conservative in comparison to those resulting from the proposed stochastic switched system approach.

Altogether, the methodology presented in this chapter can be employed to study more realistic communications effects, their interaction with control parameters and their trade-offs for fulfilling strong string stability in CACC with non-deterministic communications.

Chapter 6

This chapter demonstrates that through state estimation techniques, the communications demands of string-stable CACC vehicle pairs are relaxed. The essential notion is to replace the Zero-Order Hold (ZOH) signal reconstruction module assumed in previous chapters with a state observer. Instead of holding the last received value in-between update instants, the signal reconstruction module estimates the acceleration of the preceding vehicle.

Concretely, the state observation approach from [Plo14] involving a state-observer of the immediate predecessor is assumed for deriving a state-space model of a platoon with estimator-enhanced vehicles. The resulting platoon model is analyzed through the NCS framework presented in Section 5.1.1. The analysis yields a relaxed bound on the maximum allowed transmission interval of the string stable vehicle pairs when compared to its ZOH counterpart presented in Chapter 5.

Additionally, the estimator-enhanced platoon model is cast into the stochastic switching system framework introduced in Section 5.3. This allows to obtain the relaxed reliability requirements in terms of packet loss rates and packet reception ratios of the estimator-enhanced, strong string stable CACC.

In summary, the contributions of this chapter are obtaining an estimator-enhanced CACC model and analyzing it through the techniques presented in Chapters 4 and 5. Results show relaxed bounds on the communications requirements of estimator-enhanced, strong string stable platoons with respect to their counterparts without kinematic state observers.

Chapter 7

The main conclusions of this dissertation are drawn in this chapter. They are followed by recommendations for future research based on the findings in this thesis.

Appendices

Additional information and some proofs are reserved for the Appendices.

1.5 Already Published Content of This Work

Selected content in this work has been already published in diverse scientific publications as well as in a patent application.

- The methodology for deriving the communications requirements of the LTI CACC model presented in Chapter 4 and a previous version of the LTE-V2V SPS scheme have been published in [GFF19b] and described in the patent applications [FGC19] and [FGC21].
- The concepts describing the extension of the LTE-V2V SPS set and reducing the effective transmission period through multiple periodic sessions described Section 4.5 have been published in [GFF19a] and outlined in the patent applications [FGC19] and [FGC21].
- Results from analysis on the heterogeneity effects of CACC in the communications requirements and tradeoffs between transmission intervals and transmission delays for string stable CACC platooning as shown in Section 4.4, have been published in [GVFF19]
- The concepts and models described in Chapter 5 together with the results for the aperiodic bounds on the maximum allowed transmission intervals and the upper bounds on the tolerance towards packet losses for a string-stable platoon, have been partially published in [GVF21].