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01277 Dresden
Germany

Phone: +49-(0)351-31403921
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Bounds on Communications Resources and their Relaxation for Networked Control Systems: An Analysis on a String Stable Platoon

M. Sc.

Andrés Mauricio Villamil Sánchez

der Fakultät Elektrotechnik und Informationstechnik der
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Andrés Mauricio Villamil Sánchez
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Lehrstuhl Mobile Nachrichtensysteme
Institut für Nachrichtechnik
Fakultät Elektrotechnik und Informationstechnik
Technische Universität Dresden
01062 Dresden, Germany

Abstract

Wireless communication systems must evolve to meet the increasing demand for advanced services and connected devices. Future wireless networks aim to provide wider connectivity, enabling smarter devices to operate over broader frequency bands. This development will benefit Networked Control System (NCS) applications, including telemedicine, smart grids, teleoperation, and autonomous vehicles, with stringent latency and reliability requirements. However, a proper understanding of NCS's dynamic behavior is necessary to prevent indiscriminate communications resource usage, leading to scarcity as the number of users increases. Communications-Control Co-Design (CoCoCo) strategies would leverage the dynamic knowledge of the system to adapt the communications resource usage depending on their availability by switching between control strategies and communications policies to ensure Quality-of-Service (QoS) and Quality-of-Control (QoC).

As multiple variables parameterize the control and communications systems, the CoCoCo can be simplified by abstracting the dependencies of each design parameter on the sampling period, link latency, and packet loss probability. Determining the operation boundaries of these parameters provides a guideline to ensure the QoC based on the QoS that a communications policy can provide. Therefore, using a robustness analysis of the $\mathcal{H}_\infty$ norm of the NCS based on the imperfections introduced by the communications systems, the Maximum Allowable Transmission Interval (MATI), Maximum Allowable Delay (MAD), and Maximum Allowable Packet Loss Probability (MAPLP) can be derived. This thesis proposes a methodology for calculating MATI and deriving analytical solutions for MAD and MAPLP for general NCS. These bounds are evaluated in the longitudinal platoon case for the Cooperative Adaptive Cruise Control (CACC) case to ensure robust performance against unwanted amplified oscillations referred to as string instability.

The bounds of the communications requirements are evaluated using a Lyapunov function and a discrete stochastic transfer function, which show a close fit between the two approaches, implying an accurate estimation of the $\mathcal{H}_\infty$ norm. This work demonstrates the relevance of MATI as a normalization factor that abstracts the robustness regions of NCS and allows their comparison. The proposed methodology also shows a less conservative estimate of the MAPLP by at least one order of magnitude when the system transmits at a rate lower than the inverse of the

MATI compared to the state-of-the-art. This work proposes two control methods called Estimator Enhanced Cooperative Adaptive Cruise Control (EECACC) and Predictive CACC (PCACC) to relax the limits of the communications resources while allowing the adaptability of the CoCoCo approach. The EECACC exploits the use of Kalman filters to encode and decode the transmitted information using the estimation error and shows that, based on the assumed correlation of acceleration, the improvements over the MATI range from 21% to 238%. Conversely, the PCACC architecture evaluates how predictions can relax communications requirements and shows that predictions provide a gain that increases as the number of predictions increases. However, inconsistencies in the predictions can reduce this gain to the point where it becomes a hindrance. These different architectures provide flexibility for selecting which control strategy and communications policy guarantees the QoS and QoC of multiple users and optimally assign communications resources for NCS, laying the foundation for CoCoCo methodologies for platooning and other NCS applications.

Kurzfassung

Drahtlose Kommunikationssysteme müssen sich weiterentwickeln, um der steigenden Nachfrage nach modernen Diensten und vernetzten Geräten gerecht zu werden. Künftige drahtlose Netze werden eine größere Konnektivität bieten, so dass intelligentere Geräte in breiteren Frequenzbändern betrieben werden können. Diese Entwicklung wird Anwendungen wie Telemedizin, intelligente Stromnetze, Teleoperation und autonome Fahrzeuge zugute kommen, die hohe Anforderungen an Latenz und Zuverlässigkeit stellen. Ein angemessenes Verständnis des dynamischen Verhaltens von NCS ist jedoch erforderlich, um eine wahllose Nutzung von Kommunikationsressourcen zu vermeiden, die bei steigender Nutzerzahl zu Engpässen führen würde. CoCoCo-Strategien würden das dynamische Wissen des Systems nutzen, um die Nutzung der Kommunikationsressourcen in Abhängigkeit von ihrer Verfügbarkeit anzupassen, indem sie zwischen Kontrollstrategien und Kommunikationsrichtlinien wechseln, um QoS und QoC zu gewährleisten.

Da Steuerungs- und Kommunikationssysteme durch mehrere Variablen parametriert werden, kann CoCoCo vereinfacht werden, indem die Abhängigkeiten der einzelnen Entwurfsparameter von der Abtastperiode, der Verbindungslatenz und der Paketverlustwahrscheinlichkeit abstrahiert werden. Die Bestimmung der Betriebsgrenzen dieser Parameter liefert einen Leitfaden zur Sicherstellung des QoC auf der Basis des QoS, den eine Kommunikationspolitik bieten kann. Durch eine Robustheitsanalyse der $\mathcal{H}_\infty$-Norm des NCS auf der Grundlage der durch die Kommunikationssysteme verursachten Unvollkommenheiten können daher die MATI, MAD und MAPLP abgeleitet werden. In dieser Arbeit wird eine Methode zur Berechnung von MATI und zur Ableitung analytischer Lösungen für MAD und MAPLP für allgemeine NCS vorgeschlagen. Diese Grenzwerte werden für den Fall CACC im Längszug bewertet, um ein robustes Verhalten gegenüber unerwünschten verstärkten Schwingungen, die als Stringinstabilität bezeichnet werden, zu gewährleisten.

Die Grenzen der Kommunikationsanforderungen werden mit Hilfe einer Lyapunov-Funktion und einer diskreten stochastischen Übertragungsfunktion bewertet, die eine enge Übereinstimmung zwischen den beiden Ansätzen zeigen, was eine genaue Schätzung der $\mathcal{H}_\infty$-Norm impliziert. Diese Arbeit demonstriert die Relevanz von MATI als Normalisierungsfaktor, der die Robustheitsbereiche von NCS abstrahiert und ihren Vergleich ermöglicht. Die vorgeschlagene Methode zeigt auch eine weniger konservative Schätzung von MAPLP um mindestens eine Größenordnung, wenn das System mit einer Rate überträgt, die kleiner als der Kehrwert von MATI im Vergleich zum Stand der Technik ist. In dieser Arbeit werden zwei Kontrollmethoden, EECACC und PCACC, vorgeschlagen, um die Grenzen der Kommunikationsressourcen zu lock-

ern und gleichzeitig die Anpassungsfähigkeit des CoCoCo-Ansatzes zu ermöglichen. EECACC verwendet Kalman-Filter zur Kodierung und Dekodierung der übertragenen Information unter Verwendung des Schätzfehlers und zeigt, dass die Verbesserungen gegenüber MATI, abhängig von der angenommenen Korrelation der Beschleunigung, zwischen 21% und 238% liegen. Umgekehrt wird in der PCACC-Architektur bewertet, wie Vorhersagen die Kommunikationsanforderungen reduzieren können, und es wird gezeigt, dass Vorhersagen einen Vorteil bieten, der mit der Anzahl der Vorhersagen zunimmt. Allerdings können Inkonsistenzen in den Vorhersagen diesen Vorteil so weit reduzieren, dass er zu einem Hindernis wird. Diese verschiedenen Architekturen bieten Flexibilität bei der Wahl der Steuerungsstrategie und der Kommunikationspolitik, die QoS und QoC von mehreren Nutzern garantieren und die Kommunikationsressourcen für NCS optimal zuweisen, und legen damit die Grundlage für CoCoCo-Methoden für Platooning und andere NCS-Anwendungen.

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1

Introduction

The advancements in wireless networks, such as 5G and beyond, have brought about faster data rates and lower latency, leading to new applications with stringent latency requirements. These applications include the tactile Internet, industrial automation, telemedicine, smart grids, teleoperation, and autonomous vehicles, all of which can be classified as Wireless Networked Control Systems (WNCSs) [Fet14; Aya+19]. These types of applications leverage the use of 5G's Ultra-Reliable Low Latency Communications (URLLC) that provides small packets with low latency (around 1ms) and high reliability (packet reception rate higher than 99.999%). However, reaching this type of seamless connectivity from multiple users in a shared wireless media requires the communications system to exploit different sources of diversity that do not increase the link's latency, such as spatial diversity (the use of multiple antennas) or frequency diversity (the use of additional bandwidth) [Sch22].

The performance of the URLLC link can be aggravated if the number of users increases considerably, depleting the sources of diversity, increasing interference, resulting in a reduction of Quality-of-Service (QoS) and, in consequence, a diminution in Quality-of-Control (QoC) from the lack of updates for the control system. Moreover, the current efforts to improve reliability and latency in the development of future wireless networks (6G and beyond) [Pop+22] will only over-provide communications resources to WNCS if it does not effectively adjust to the demands of the control system.

Therefore, there is a need for interfaces between the control and communications systems that allow network-aware controllers to inform their communications requirements and control-aware networks to notify of its availability while ensuring both QoS and QoC [FB21; GVF21; Gon22]. As a first step in this Communications-Control Co-Design (CoCoCo), it is vital to assess the boundaries of the communications requirements of the control system. This evaluation should consider imperfections in the wireless link, such as transmission intervals, link latency, and packet losses [Par+17]. Each communication policy must be evaluated to ensure it falls within the established bounds, and the communication system will determine which policy to implement.

Designing controllers that can handle communication link imperfections can help optimize the wireless network performance. One approach is to use predictive controllers that leverage model prediction to anticipate the system's dynamics while adapting to possible packet losses, as shown in [Ona+10; Que+15; PQØ15]. Alternatively, estimators like the Kalman filter provide a methodology to estimate missing information due to packet losses using the available information, as demonstrated in [Sch+07; SEM10; Liu+21]. Another strategy involves a switching controller that depends on the number of packet losses or delays, as seen in [Clo+10; LZQ18; SSH23]. The design of other controllers involves considering the effects of random delays and packet losses in the cost function for finite horizon optimal control [Mai+21] or using receiver acknowledgments to adapt the controller [Zac+23]. In [Mam+20b], an optimization algorithm is proposed to assign communications resources to multiple Cyber-Physical Systems (CPSs) depending on the availability and the communications' service price.

All of these control architectures can reduce the consumption of communications resources, expanding the communications requirements bounds, and freeing up these resources for other systems to use if required. Understanding the interdependent relationship between control and communications can enable the creation of more efficient WNCS [SBC19]. The resulting question is: *How can both systems (Communications and Control) be designed together such that the usage of communications resources is optimized and ensures the QoC?*

1.1 Control-Communications interdependent design variables

In order to streamline our communications system's description, this work focuses on the capabilities of 5G New Radio (NR) release 16, particularly its provision of URLLC (designed for WNCS [ETS18]), and the availability of sidelink in Vehicle-to-Everything (V2X) communications, which allows the devices to communicate directly without relying on a base station [Har+21]. These assumptions drive the research towards autonomous driving use cases, leading this work to focus on the platooning use case in the CoCoCo context.

Although it is possible to optimize multiple variables of control and communications systems individually to improve either the Networked Control System (NCS)'s capacity to operate under poor QoS or the network's ability to provide better QoS for a simpler control strategy, it is essential to understand the parameters that affect both systems to address their challenges effectively. According to [Par+17], the primary co-design variables for CoCoCo are:

1. Sampling period
2. Link Latency
3. Packet Loss Probability
4. Energy Consumption

The following sections describe each of these variables.

1.1.1 Sampling Period

The sampling period determines the frequency at which a control system collects or generates new data. It can be determined by how often sensors gather information or how frequently the controller calculates a new control signal. A periodic scheme can be represented by a discrete system [FPW+98] or event-based schemes are based on a control variable or Lyapunov function exceeding a threshold [Dem+16; Mam+20a; Var+23]. This approach can save communication resources by avoiding unnecessary updates when changes in the control signal are insignificant. However, the triggering condition must be appropriately designed, or it may result in increased communication resource usage compared to the periodic scheme if not optimized. A combination of both approaches may be more appropriate, depending on the data traffic generated in the system. In the worst-case scenario, with high data traffic, the control system could use periodic transmission, with the event-triggered scheme, during less demanding periods. Fig. 1.1 illustrates this approach.

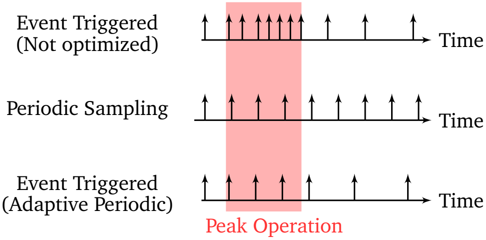

Fig. 1.1.: Representation of the transmission traffic from a periodic sampled controller and two event-triggered controllers: a non-optimized version that generates more updates than the periodic scheme, and an optimized version that, its worst traffic is the same as the periodic scheme.

This work considers that the transmission interval of packets is equivalent to the sampling period for communications systems (notice that it is different from the data rate at which packets are transmitted). The network determines this interval and can be either periodically scheduled or dynamically determined depending on the technology and mode of operation. These modes of resource allocation are available in V2X communications [Lie+20] while the structure of the OFDM waveform will determine the minimum transmission interval in 5G NR. The transmitted waveform can be abstracted into a Time-Frequency resource pool in a grid shown in Fig. 1.2. The minimum number of symbols per slot is 14 with a duration of 2^{-n} [ms] and a bandwidth of $2^n \times 15$ [kHz], where $n \in \{0, 1, 2, 3\}$ determines the numerology of the wireless link [Gar+21]. The packet duration also depends on the chosen Modulation and Coding Scheme (MCS), which determines the number of bits packed in a symbol and the number of redundant bits for error correction. Therefore, the combination of numerology, MCS, and the number of transmitted bits determine the packet duration. Since the system can only transmit one packet at a time, the minimum transmission interval will be equal to the packet duration. However, selecting this sampling would be inefficient with the communications resources as the system would constantly transmit, and reducing the transmission interval would require additional bandwidth.

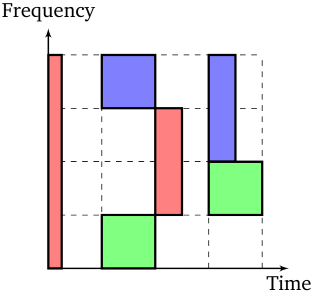

Fig. 1.2.: Representation of the time-frequency grid for Orthogonal Frequency Division Multiplexing (OFDM) with three different users (depicted in different colors: red, blue, green) using different numerologies to transmit packets.

1.1.2 Link Latency

The modeling of control systems latency refers to the time delay between the generation and arrival of a signal. Although this delay may not significantly impact the magnitude response of the system, it can affect the phase, reducing the phase margin that ultimately lead to the instability in the control system [Oga+10].

In NCS, the primary source of latency is the communications system, which can be categorized into three sources of delay [Par+17]: the **transmission delay**, the **Medium Access Control (MAC)**, and **information relaying**. For V2X communications, it can be described as:

- Transmission delay: packet duration, encoding, and decoding time.
- MAC: In 5G NR, resource allocation is carried out in either controlled or autonomous mode [Baz+21; Lie+20], with both modes offering dynamic or periodic resource distribution. Coordination between the base station and the vehicles requires multiple packet transmissions, which adds to the overall latency. Additionally, resource allocation depends on channel measurements, which introduces further delay (it can be reduced by preemptively doing the measurements of a time window). The sensing phase is negatively impacted by the number of users sharing the wireless link, and the resource pool can reserve some resources for re-transmission to increase the transmitted packet's reliability. Although this may not always benefit the control system [WY01] and can be used if low latency is not a requirement.
- Information relaying: When a packet needs to be sent to multiple nodes in a network, but there is no direct communication link to all nodes, the information must be relayed through different network nodes. However, this introduces additional sources of delay, which increase with each additional node. It is worth noting that in release 16, relaying is only available between devices that close to the same base station. The upcoming release plans to address this limitation, enabling relaying between different devices and providing greater flexibility in packet transmission at the cost of increased latency [Baz+21].

1.1.3 Packet Loss Probability

The randomness in the packet reception makes the NCS model stochastic. As a result, the control system has to decide how to proceed when packets are lost. One approach is to wait until the next update is received, while another option is to use the last received sample until the next one becomes available [Van+17]. A more proactive strategy is to use estimators to compensate for the lost information

[Plo+14] or to use predictive controllers and predictions as an additional source of information for the controller [Que+15].

On the communications side, the physical wireless channel's condition determines the probability of packet reception, which depends on the received Signal-to-Noise Ratio (SNR) magnitude and MCS [Tod+21]. Additionally, packet reception can be disturbed by interference from external sources, and packet collisions may occur randomly with dynamic resource allocation. Consequently, channel estimation algorithms are used in communication systems to determine time-frequency grid blocks with a high probability of being received with a high SNR [Tod+21; Gar+21].

The URLLC literature defines *packet loss probability* as the likelihood that a packet will not be received by its deadline [Pop+19]. These losses can occur if a packet is transmitted later than expected or the communications systems do not immediately find a free and reliable communications resource. This idea can be introduced into NCS to remove time-varying delays and reduce the complexity of the control model by assuming that if the information is received beforehand, the control system can hold the information up to the deadline. Otherwise, the packet is considered lost, and the control system waits for the following update [FB21]. In situations that require high reliability, this deadline can be used to attempt multiple transmissions to increase the probability of reception.

Furthermore, suppose multiple nodes must transmit simultaneously, and the available bandwidth is scarce. In that case, these transmissions will compete against each other, leading to increased interference and decrease QoS and QoC. Therefore, knowledge of the incoming data traffic can help distribute the communications resources more efficiently, or the control system can be adjusted to tolerate more extended periods without control updates to reduce the packet loss probability.

The stochastic fluctuations are caused by various factors such as multi-path propagation, fading, and shadowing. These effects have been modeled into Markov chains in [Sad+08] and the references therein. Although these analyses were done on the symbol level, extending them to packet description is possible if the SNR ratio remains constant throughout transmission and packets have small payloads. It requires two conditions: First, the packet duration must be shorter than the coherence time, which is the time period during which all symbols are correlated for a duration of approximately the inverse of the Doppler spread:

$$f_d = \frac{v}{c} f_c,$$

where c is the speed of light, v is the relative velocity between the receptor and the transmitter, and f_c is the carrier frequency of the transmitted wave. Secondly, the used bandwidth has to be less than the coherence bandwidth, i.e., the frequency response of the channel is considered to be flat (same received SNR) if the bandwidth is lower than the inverse of the maximum delay spread [SA01].

Moreover, the use of a Markov chain to model the communications channel can be connected to the formalism of Markov Jump Linear System (MJLS) where mathematical operators are used to determine the QoC of the NCS [AQ21; VGF22], for example, the Mean Square Stable (MSS), $\mathcal{H}_\infty$ norm [SS05], among others. In contrast, [YFX11; QAJ12] used the Markov chain to determine the possibility of estimation under packet losses due to fading, [Lun+20] proposed a Markov chain to represent the performance of WirelessHART and derived a methodology to produce a controller, and [Par19] calculated mean input delay and mean time to failure of a fault-tolerant WNCS using a Markov model.

1.1.4 Energy Consumption

Increasing the complexity of controllers requires more computing power, which can be a scarce resource in low-power distributed devices. For example, a Model Predictive Controller (MPC) needs to solve an optimization problem at each sampling period, which adds extra computational burden. In this scenario, offloading the additional computation to the edge cloud of a 5G network can be a viable solution. This can lead to a reduction in packet losses with a slight increase in latency, as the base station is not bound by strict power requirements and can broadcast the information to all devices. This approach can be particularly useful for distributed systems with limited computing capabilities [HYW19].

Decreasing power consumption is critical for extending the lifespan of wireless sensor networks and can be achieved by minimizing the number of transmissions and reducing radio circuit usage. However, a denser coding scheme increases power consumption in Analog and Digital converters. Hence, there is a trade-off between power consumption and packet duration, assuming the same bandwidth usage.

The reduction of transmission implies that the information in the NCS will be used for more extended periods. The Age-of-Information (AoI) is a metric to quantify this time. Typically, networks aim to minimize the AoI to guarantee the arrival of *fresh* information with the limited available communications resources [KSM19]. However, whether fresh packets are always necessary to ensure the QoC of an NCS is worth considering. This idea poses an alternative solution where the network leverages the robustness of the control system to maximize the average Peak Age-of-Information (PAoI), reducing the number of transmissions while guaranteeing the QoC. Reducing radio resource consumption would help free up resources that can be assigned to other communications links, reducing the probability of interference and increasing the number of devices the network can manage at the cost of reducing the robustness to imperfections of the wireless link.

1.2 Codesign Optimization Problem

Considering the design variables previously described and their interplay in the performance of the NCS, it is possible to formulate a codesign optimization problem. The solution would select the optimal "*communications-control*" design variables (sampling period τ_s^*, link latency τ_d^* and packet loss probability β^*) determined by the communications policy π_{cm}^*, and the control strategy π_{ct}^* based on a specific cost function. A simple formulation of this codesign would be to evaluate from the set of available communications policies (Π_{cm}) and control strategies (Π_{ct}), the parametrization that optimizes the cost function subject to the QoC. Such an approach would need:

1. The inclusion of the codesign variables in the state space of the control system π_{ct} represented as $\mathcal{F}_{\pi_{\text{ct}},(\tau_s,\tau_d,\beta)}$.
2. The representation of the QoC as constraints $f^{(j)}(\mathcal{F}_{\pi_{\text{ct}},(\tau_s,\tau_d,\beta)}) \in \{0,1\}$, where $f^{(j)}(\cdot) = 1$ represents that the constrain is fulfilled and $j \in \{1,\ldots,N_{\text{const}}\}$ is the number of constraints. The constraint that would always be included is the stability of the system and would always represent the index j=1.
3. The computation of the set of feasible communications parameters of control strategy π_{ct} denoted by: $\mathcal{C}(\tau_{\text{MATI}}^{\pi_{\text{ct}}}, \tau_{\text{MAD}}^{\pi_{\text{ct}}}, \beta_{\text{MAPLP}}^{\pi_{\text{ct}}})$.

The variables that define the feasible region of communications parameters in 3. represent the boundaries of the communications requirements and are referred to as:

- $\tau_{\text{MATI}}^{\pi_{\text{ct}}}$: Maximum Allowable Transmission Interval (MATI)
- $\tau_{\text{MAD}}^{\pi_{\text{ct}}}$: Maximum Allowable Delay (MAD)
- $\beta_{\text{MAPLP}}^{\pi_{\text{ct}}}$: Maximum Allowable Packet Loss Probability (MAPLP)

This approoch will benefit if the dependencies between τ_s, τ_d, and β are understood and would help understand the following question: *how does a control strategy ease the communications requirements of an NCS while ensuring its QoC?*

To optimize the network usage and following the arguments from the previous section, the average PAoI can be used as a cost function to minimize the use of communications resource, i.e., maximize $\mathbb{E}\{\text{AoI}_{\text{peak}}\}$. For simplicity, it is assumed that the latency corresponds only to the latency generated by the communications systems. Other sources of delay, namely, data acquisition and control signal computation, are assumed to be zero. In this manner, the definition of link latency and communications deadline can be used interchangeably. Another assumption to simplify the analysis throughout this work is that the transmission interval $\tau_s^{\pi_{\text{cm}}}$ is periodic and mostly equal to the sampling period of the control system. The optimization problem can be defined as:

Optimization Problem. 1.2.1: Communications-Control Co-Design (CoCoCo)

$$\begin{aligned}
(\pi^*_{\text{cm}}, \pi^*_{\text{ct}}) = \text{argmax} \quad & \mathbb{E}_{(\pi_{\text{cm}}, \pi_{\text{ct}})}\{\text{AoI}_{\text{peak}}(\tau_s^{\pi_{\text{cm}}}, \tau_d^{\pi_{\text{cm}}}, \beta^{\pi_{\text{cm}}})\} \\
\text{s.t.} \quad & \pi_{\text{cm}} \in \Pi_{\text{cm}} \\
& \pi_{\text{ct}} \in \Pi_{\text{ct}} \\
& f^{(j)}(\mathcal{F}_{\pi_{\text{ct}},(\tau_s^{\pi_{\text{cm}}}, \tau_d^{\pi_{\text{cm}}}, \beta^{\pi_{\text{cm}}})}) = 1, \quad \forall j \in \{1, N_{\text{cons}}\} \\
& \{\tau_s^{\pi_{\text{cm}}}, \tau_d^{\pi_{\text{cm}}}, \beta^{\pi_{\text{cm}}}\} \in \mathcal{C}(\tau^{\pi_{\text{ct}}}_{\text{MATI}}, \tau^{\pi_{\text{ct}}}_{\text{MAD}}, \beta^{\pi_{\text{ct}}}_{\text{MAPLP}})
\end{aligned}$$

The solution of Optimization Problem 1.2.1 finds a communications policy π_{cm} that reduces the usage of the wireless link while ensuring that its QoS ensures the QoC conditions. Obtaining the region $\mathcal{C}$ determined by MATI, MAD, and MAPLP is key for the solution of the codesign problem since it decouples the specifics of the control and communications systems. The different control strategies determine its communications requirements based on the QoC restrictions and the communications systems need to guarantee that its QoS is within the region.

This work uses Cooperative Adaptive Cruise Control (CACC) case to understand the CoCoCo problem since it is a well-studied NCS. This use case, depicted in Fig. 1.3, consists of the longitudinal control of the intervehicle distance between autonomous vehicles using a velocity-dependent spacing policy determined by the headway time. The control strategy consists of a Proportional-Derivative (PD) control and a feedforward control that uses the information of the preceding vehicle in the platoon. As [Swa+94] showed, using only radars leads to undesired oscillations if the headway time is low. However, this effect is removed by the inclusion of the control signal of the previous vehicle that is transmitted through the wireless link [Nau+10]. The lack of amplified oscillations throughout the platoon is referred to as string stability and can be mathematically defined as ensuring that the $\mathcal{H}_\infty$ norm from the control signal of a vehicle in the platoon does not amplify the control signal of its follower. The work in [PVN13; Önc+14] showed that the gain between the leader and the last vehicle of the platoon can be factorized by the individual gains between vehicle pairs in the platoon, allowing to focus on the study of the $\mathcal{H}_\infty$ condition between two adjacent vehicles in a platoon to determine the communications requirements of the control application.

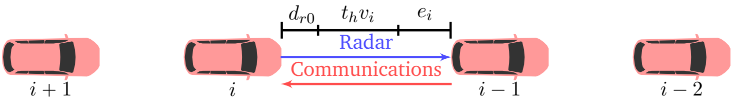

Fig. 1.3.: Longitudinal platoon problem representing the velocity-dependent spacing policy of Cooperative Adaptive Cruise Control to regulate the intervehicle distance. In this case, i is the vehicular index in the platoon, d_{r0} is a stand-still spacing, t_h is the headway time, v_i is the velocity of vehicle i, and e_i is the intervehicle distance error.

Previous work, as summarized in Tab. 1.1, has investigated methodologies to obtain the communications requirements of NCS. In [WYB02], a control network protocol was introduced where sensors and actuators had to transmit information before the MATI. This approach proved the conditions for a globally exponentially stable NCS but it provided a conservative estimation of the MATI. An alternative was introduced in [Hee+10] by using a Lyapunov function with a differential equation to calculate the MATI and MAD that ensure the stability and an $\mathcal{H}_\infty$ bound of the NCS with aperiodic transmission and random delays. Meanwhile, the work presented in [Nau+10] studied different control conditions to compute the feasibility of string stability and the MAD for CACC. The work presented in [Önc+14] applies the theory from [Hee+10] into CACC and evaluates the requirements for the discrete system with periodic transmission. It is important to note the effort to relax the dependency on the communications systems by the introduction of Kalman filters into the control loop to estimate the dynamic behavior of the preceding vehicle introduced in [Plo+14]. In [DPH17], an event-triggered communications scheme was developed for CACC to select when an update is relevant to transmit. The work in [XPN19] used a Smith predictor to deal with the link latency and reduce the minimum possible headway time. An extension to the work of [Hee+10] was introduced in [Hei+18; Hei+20] where a minimum allowable transmission interval is computed to relax the conditions of the MATI. The work in [Ibr+21] uses an Model Predictive Control (MPC) for the multi-rate system that distinguishes between the sampling of the in-vehicle control and the transmission intervals of the communications system. Finally, in [Gon+19], it was proposed to model the wireless link as a Zero Order Hold (ZOH) with delay and using a Padé approximant to obtain the MATI and MAD as the roots of polynomials that ensured a $\mathcal{H}_\infty$ norm requirement. This approach was later extended to account for packet losses as well in [GVF21; Gon22] by modeling the link as a stochastic switching system. Although the aforementioned work has improved the calculation of MATI and MAD, there is still a gap in determining the MAPLP without requiring high reliability from the wireless link.

In contrast, the communications systems community has been working on future releases of wireless networks to introduce mechanisms that enable autonomous driving by improving the capabilities of the network for V2X communications, focusing on the sidelink (see [Baz+21] and references therein), i.e., a direct link between vehicles rather than with a base station intermediary. The design of these networks has specific communications requirements depending on the application, e.g., $\tau_s = 1/30$ [ms], $\tau_d = 10$ [ms], and $\beta = 0.01\%$ for autonomous driving [ETS20]. However, there is no apparent criterion for selecting these parameters [GVF21], and each parameter can not be adapted depending on the controller design or the number of users that share the wireless media. This lack of deeper understanding from the developments of 5G and beyond technologies on the communications requirements for control applications, and the static approach to provide communications resources to NCS applications, creates the opportunity to design efficient CoCoCo techniques that generate useful interfaces to integrate communications and control while using both systems efficiently.

The goal of this work is to determine less conservative analytical bounds for MATI, MAD, and MAPLP, and to understand their relationship when changing the control strategy. This analysis is achieved by assuming periodic transmissions with a predetermined fixed deadline; packets that arrive before this deadline are considered successfully transmitted and used at the deadline. Hence, this work focuses on solving two main questions:

1. *What is the relationship between the control strategy and the feasible region of communications requirements $\mathcal{C}(\cdot)$ for a NCS with periodic transmission that ensures the QoC?*
2. *Which control strategies relax the communications requirements to expand the feasibility region $\mathcal{C}(\cdot)$ in order to increase the robustness and flexibility of CoCoCo?*

Reference	MATI	MAD	MAPLP	Methodology
[WYB02]	✓	✗	✗	Introduces the notion of communications requirements for NCS and proposes a Lyapunov approach to calculate the MATI.
[Hee+10]	✓	✓	✗^{1}	Uses a Lyapunov function to calculate the MATI and MAD for random delays and $\tau_{\text{MATI}} \geqslant \tau_{\text{MAD}}$. General for nonlinear systems.
[Önc+14; Önc14]	✓	✓	✗	Proposes a discretization of the state space of CACC and numerically evaluates if the sampling and delay guarantees string stability.
[DPH17]	✓	✓	✗^{1}	Proposes a Lyapunov function to generate an event trigger controller that fulfills the string stability of the platoon and determines the MAD and the Minimal Inter Event Time. Also considers that $\tau_{\text{MATI}} \geqslant \tau_{\text{MAD}}$ and random delays.
[Gon+19]	✓	✓	✗	Introduces a ZOH transfer function to establish through a Zero-Pole analysis the MATI and MAD that guarantee the string stability.
[GVF21; Gon22]	✓	✓	✓*	Introduces a switching system to calculate the MAPLP based on the rates given in [Gon+19]. The first publication

Tab. 1.1.: State of the art methodologies to calculate the communications requirement bounds and their restrictions with emphasis in CACC. ✗^{1} refers to studies where packet losses are not considered, but assume that there is an upper bound on the number of consecutive packet losses, and the transmission interval must be reduced by that factor. ✓* calculates a MAPLP, but is conservative for any transmission interval.

1.3 Contributions and previous published work

The foundation of this work is based on [Gon22], which presents methodologies for computing communication requirement bounds for CACC. Additionally, multiple publications ([Vil+19], [Vil+20], [VGF21], [VGF22], [VGF23]) were made with the author's guidance, and the primary contributions of these publications, made by the author of this thesis (*Bounds on Communications Resources and their Relaxation for Networked Control Systems: An Analysis on a String Stable Platoon*), are summarized in the following list of published work.

- Introduces the effects of communications links, namely, sampling period, delay, and packet losses, to discrete systems models using Markov Jump Linear System for the determination of communications requirements bounds (Maximum Allowable Transmission Interval, Maximum Allowable Delay, and Maximum Allowable Packet Loss Probability) proposing a close form solution for MAD and MAPLP when imposing the $\mathcal{H}_\infty$ norm constraint using Lyapunov functions with Linear Matrix Inequalitys (LMIs) and a average discrete state space [VGF22; VGF23].

- Uses the Peak Age-of-Information to derive the MAPLP based on linear dependencies to transmission interval and delay [VGF23].

- Proposes and evaluates the performance of a new architecture, Estimator Enhanced Cooperative Adaptive Cruise Control (EECACC), to increase the communications requirements bounds by using Kalman filters to estimate the dynamic behavior of the transmitted signal and the transmission of the estimation error for CACC [Vil+19; VGF21].

- Shows that the MATI abstracts the communications requirements bounds of the discrete control system and allows a comparison between different systems by the normalization of MAPLP and PAoI, regardless of the different parametrization in the control system.

- Evaluates the usage of predictions to increase the communications requirements bounds in Predictive CACC, finding an algorithm to compute the MAPLP and close form solution for MATI and MAD while also showing the degraded performance from erroneous predictions

1.4 Thesis Outline

This work is comprised of five additional Chapters, which can be categorized into three parts. The first part focuses on the theoretical modeling of general Networked Control System (NCS), as shown in Chapter 2. It outlines a control architecture that contains an internal feedback loop and a feedforward controller that uses the wireless link to transmit its updates. This general structure is used to model the NCS using the Markov Jump Linear System (MJLS) formalism to include the stochastic nature of packet losses, including the link latency and the discrete nature of the transmission of packets to study its stability and its $\mathcal{H}_\infty$ norm. It provides an algorithmic way to calculate the Maximum Allowable Transmission Interval (MATI) and two methodologies to estimate the $\mathcal{H}_\infty$ norm using a discrete mean transfer function and a Lyapunov approach. It derives the relationship between MATI and MAD, followed by the definition of Peak Age-of-Information (PAoI) for this type of Networked Control System and a theoretical model of Maximum Allowable Packet Loss Probability (MAPLP) by considering some conditions on PAoI.

The second part consists of Chapter 3, 4, and 5, where the communications requirements of different control strategies are evaluated using the theoretical model shown in Chapter 2. Chapter 3 introduces the CACC model with the string stability constraint and the communications requirement bounds. In Chapter 4, the Estimator Enhanced Cooperative Adaptive Cruise Control (EECACC) architecture is shown, in which Kalman filters estimate the transmitted information, and the enhancement comes for transmitting the estimation error instead of the control signal to relax the communications requirements. Finally, a Predictive CACC (PCACC) system is proposed to understand the effects of predictions on the boundaries of the communications requirements in Chapter 5. It shows that, although MAD do not change, the MAPLP can be improved depending on the number of transmitted predictions. Moreover, an algorithm is proposed to estimate the improved MAPLP value. This Chapter also shows the effects of using wrong predictions in the packet loss probabilities and how it harms the system's performance.

The third part consists of Chapter 6, which summarizes the findings and outlook of this work.

Part I

Theoretical Analysis of Communications Requirements for Wireless Networked Control System