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Theme:

Event-triggered control strategy for large-scale industrial systems via Fieldbus protocols

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Amine Ala Eddine TEFFAHI

Abbreviations

CA	Collision Avoidance
CD	Colllision Detection
CIP	Common Industrial Protocol
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access
CSTRs	Continuous stirred-tank reactors
DCS	Distributed control system
ETC	Event Triggered Control
ETM	Event Triggered Mechanism
EVs	Electric Vehicules
FCS	Frame Check Sequence
FIFO	First In First Out
IE	Industrial Ethernet
LCs	Local Controllers
LFC	Load Frequency Control
LMIs	Linear Matrix Inequalities
LSSs	Large Scale Systems
LTI	Linear Time Invariant

MAC	Media Access Control
MAIB	Maximum Allowable Imperfections Bound
METC	Modified Event-Triggered Control
NCS	Networked Control System
OSI	Open Systems Interconnection
PLC	Programmable Logic Controller
QoS	Quality of Service
RTU	Remote Control Unit
SCADA	Supervisory Control And Data Aquisition
SSID	Service Set Identifier
SSs	Subsystems
TCP/IP	Transmission Control Protocol/Internet Protocol

Abstract:

This Memoir presents a comprehensive investigation into the development and implementation of an event-triggered control strategy for large-scale systems via fieldbus protocols, ensuring system stability and optimizing control performance in the presence of network-induced imperfections. Giving a comprehensive overview of large scales, and their modeling methods and problems. The design methodology incorporates the selection of appropriate event conditions, trigger parameters to achieve the desired system performance while minimizing network utilization. The conditions obtained are tested using numerical illustrative examples representing different LSSs with network-induced delay, as well as a comparison with other existing methods in terms of robustness.

Keywords: Event-triggered control, Large-scale systems, Networked control systems, Fieldbus protocols, Network-induced delay and external disturbances.

ملخص:

تقدم هاته الأطروحة بحثا معمقًا في تطوير وتنفيذ استراتيجية التحكم التي يتم تشغيلها بواسطة الحدث للأنظمة واسعة النطاق بواسطة بروتوكولات الاتصال الصناعية، مما يضمن استقرار النظام ويحسن أداء التحكم في وجود عيوب ناتجة عن الشبكة . تتضمن منهجية التصميم اختيار ظروف الحدث المناسبة وشروط التشغيل لتحقيق أداء النظام المطلوب مع تقليل استخدام الشبكة. يتم اختبار الشروط التي تم الحصول عليها باستخدام أمثلة توضيحية رقمية تمثل LSSs مختلفة مع تأخير الناجم عن الشبكة ، بالإضافة إلى مقارنة مع الطرق الأخرى الموجودة من حيث المتانة.

الكلمات المفتاحية : التحكم المشغّل بالحدث، الأنظمة واسعة النطاق، أنظمة التحكم الشبكية، البروتوكولات الصناعية، التأخير الناجم عن الشبكة ، الاضطرابات الخارجية.

Résumer :

Ce Mémoire présente une enquête approfondie sur le développement et la mise en œuvre de une stratégie de contrôle déclenchée par un événement pour les systèmes à large échelle par des protocoles de bus de terrain, garantissant que le système stabilité et optimisation des performances de contrôle en présence d'imperfections induites par le réseau. La méthodologie de conception intègre sélection des conditions d'événement appropriées, des paramètres de déclenchement pour atteindre les performances système souhaitées tout en minimisant l'utilisation du réseau. Les conditions obtenues sont testées à l'aide d'exemples illustratifs numériques représentant différents LSS avec retard induit par le réseau, ainsi qu'une comparaison avec d'autres méthodes existantes en termesde robustesse.

Mots clés : Contrôle déclenché par événement, Systèmes à grande échelle, Systèmes de contrôle en réseau, Protocoles de bus de terrain, Retard induit par le réseau et perturbations externes.

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Chapter 1

General Introduction

The expansion of the contemporary industry has led to the immense growth of processing systems, increasing their complexity, designing control systems for these industrial systems has become significantly challenging due to their rapid and inevitable development. Between the common complex industrial system is the large-scale systems (LSSs) which are comprised of numerous interrelated subsystems (SSs) which are also spatially distributed in the area and characterized with its local controllers (LCs), where each subsystem operates has a local controller (LC) to manage its specific functions within the larger system. When it comes to LSSs, they have become an integral system in multiple sectors, including integrated chemical manufacturing, supply chains, transportation networks, and power grids. These systems heavily rely on a diverse range of control techniques, communication protocols, and monitoring systems to ensure effective and secure operations. To tackle the challenges associated with such systems, experts have put forward several strategies, namely distributed control algorithms, supervisory control techniques, and networked control systems. DCS, SCADA, are examples of real large-scale systems of the most widely used, Where SCADA systems are used to monitor and control large-scale processes or facilities, whereas DCS is a decentralized control system that spreads control functions over different subsystems in specific architecture, and its components are physically interconnected through a single digital real-time communication channel, that connects the control loop components (sensors, actuators, and controllers). There are different communication protocols used in large-scale systems called Fieldbus protocols such as MODBUS, HART, CAN, and industrial Ethernet that able devices to connect in the same communication network. MODBUS is an open-source protocol that allows for communication between devices, while HART is used to transmit digital and analog signals between field

devices and a control system. CAN is widely used in the automotive industry for communication between various electronic systems in a vehicle. Furthermore, Ethernet is often used as a backbone to connect various subsystems and devices to a central control system. However, the complexity of the network control system and the deleterious effects of the transmission channel can cause communication delay, packet loss, and packet disordering. These issues can lead to a loss of data, which can affect the system's performance and safety. To overcome these challenges, as we mentioned previously various control mechanisms and communication strategies have been proposed such as for example Event-triggered, and self-triggered control strategies which are used to improve the quality of control via the communication network by reducing the unnecessary transmitted packets [6, 12, 75].
At the end of this introduction, we can just say that complicated systems need effective and secure monitoring techniques, robust control protocols, and intelligent control methods.

1.1 Historical Review

Large-scale control systems have been used in various industries, the history of industrial automation dates back to the 1920s, with the introduction of mass production and programmable machine tools. Implementing controls for these systems is a major challenge, and the use of distributed control methods has become a popular technique for managing the size and interactions of these complex systems [73]. The development of these systems can be traced back to the 1950s when the first digital computer systems were introduced. Over time, automatic control systems were introduced to monitor and regulate industrial processes. Automatic control systems evolved from centralized control systems to distributed control systems as complexity and connectivity requirements increased [27]. Large-scale industrial system architectures are often composed of several interconnected subsystems as we said previously. Control of such systems is usually decentralized to avoid bottlenecks in data communication. Commonly used control structures include decentralized, distributed, and hierarchical structures [27] [7]. Distributed control algorithms for actuation, estimation, and monitoring are used to solve control problems of large-scale interconnected systems. These algorithms are used to regulate the dynamics of these systems while minimizing communication and computational costs. Recent results have shown that the predictive model method Distributed MPC is an effective distributed control technique for these systems [54]. As we mentioned, one example of LSSs is DCS and it was introduced in the 1970s as a replacement for traditional PLC(Programmable Logic Control) centralized control systems. The first DCS systems were used in the process industries, such as petrochemicals, chemicals, and power generation. In recent decades, Large-scale systems or Distributed control systems have become increasingly popular due to their advantages over traditional control systems, such as increased performance, flexibility, and scalability. However, the history of communication between subsystems in an NCS has not always been smooth. Initially, communication between subsystems was achieved using periodic transmissions, which had several drawbacks, including poor response times, wasted bandwidth, and the potential for data collisions. In recent decades, great effort has been devoted to modeling, stability analysis, and control design of Large-scale systems due to the existence of different network-induced imperfections which need analysis and synthesis methods including all these imperfections. Unfortunately, much of the available literature research on NCSs has considered some types of network imperfections and ignored the other types where it is important to consider that the design of a typical LLC requires trade-offs between the different imperfections types. For example, reducing quantization errors leads to larger transmission delays which means that it is necessary to do the trade-offs between these two imperfections to get a good quality of service (QoS). Therefore, it is important to improve and integrate the available results to obtain a framework in which all the network-induced imperfections can be studied simultaneously with the possibility of trade-offs made.

There exist two different ways to model network-induced imperfections, the first one is the deterministic method which assumes a bounded model on the time delays, the number of packet loss, and sampling intervals where all possibilities of random processes are ignored [11, 36, 63, 66]. The second class of methods uses the stochastic information nature of the network-induced imperfections to model the NCSs [9,37,41,46,55,58,62,72]; [10,43,49]. Several NCSs models appeared in the literature resulting from these two methods (eg., switched system approach, impulsive system approach, sampled data approach, and stochastic approach). The study of the stability problems of Large-scale systems is a crucial objective in the control field where the main goal is to reduce the effect of the network-induced imperfections on stability by ensuring maximum allowable imperfections bound (MAIB) guaranteeing the stability of the closed-loop and achieve good performance(eg., guarantee a maximum allowable delay bound, the maximum packet dropouts, the maximum quantization error). Consequently, the MAIB becomes a key performance index to reduce the conservatism of the stability con-

ditions. . To achieve this goal, different interesting methods have been proposed to reduce the conservatism of the stability criterion mainly by constructing a new Lyapunov-Krasovskii and using or developing lemmas to estimate its time derivative [42]; [65]; [20]; [50]; [22].
Over the years, Large-scale systems have undergone advancements through the introduction of recent control strategies. Among these strategies are the Event-triggered control strategy, and self-triggered control strategy, which have aimed to enhance communication and control efficiencies within LSSs by optimizing the utilization of network resources and reducing the number of transmissions [19], [5]. The traditional approach of time-triggered control involves executing control actions periodically at fixed time intervals. This method provides determinism and simplicity in system design but may result in sub-optimal resource utilization as control actions are performed regardless of the system's actual state or event occurrences [21]. In contrast, event-triggered control offers a more efficient use of network resources by triggering control actions based on specific events or conditions. This approach aims to reduce unnecessary transmissions by transmitting data only when necessary. Event-triggered control has gained significant attention in resource-constrained systems due to its advantages. It can be tailored to various factors, such as system dynamics, measurement error, or desired performance criteria, allowing for customizable trigger conditions. This flexibility contributes to its appeal and widespread research interest ([19], [5]). The ETS offers a practical approach for determining the optimal instances to sample and transmit data, thereby minimizing the volume of transmitted data and optimizing resource utilization. To gain insights into the historical context of event-triggered control strategies in NCSs, let us delve into the web search findings presented. In an influential paper published in 2015, the authors conducted a comprehensive survey of advancements in event-triggered control schemes specifically designed for networked control systems. This paper explores the conceptual framework of ETC, emphasizing the co-design of the controller and communication scheme, and introduces the concept of distributed event-triggered control [19]. Subsequently, a paper from 2016 accentuates that event-triggered control ensures that only essential state signals are transmitted to the controller, consequently reducing the amount of data sent [71]. A noteworthy paper published in 2021 proposes an innovative event-triggered method applicable to switched systems, allowing for multiple systems switches over an event-triggered interval. The primary focus lies in the finite-time extended dissipative analysis of closed-loop networked switched systems [15]. Another paper investigates the event-triggered control strategy for robot manipulators operating in com-

munication networks. It delves into the dynamic equations, the operational state of the event trigger, and the utilization of sliding mode and cognitive controllers to ensure stability and mitigate the repercussions of Denial-of-Service (DoS) attacks [56]. In a 2021 article, researchers present an event-triggered control strategy tailored for networked systems facing hybrid attacks and limitations in network resources. A novel event-based model for networked control systems is established in this work [31]. Lastly, a recent paper from 2023 proposes the integration of the event-triggered disturbance estimation and rejection (DER) technique with the networked predictive control (NPC) strategy for networked control systems subject to external disturbances and time delays [64]. The findings from these web search results unmistakably demonstrate the extensive study and exploration of event-triggered control within the historical context of networked control systems. This strategy aims to reduce data transmission, optimize resource utilization, and tackle challenges such as system switching, DoS attacks, hybrid attacks, and external disturbances. Self-triggered control is a strategy that combines aspects of both time-triggered and event-triggered control. It executes control actions when certain events occur or specific conditions are met, similar to event-triggered control. Additionally, it incorporates a periodic component where control actions are executed periodically if no triggering events occur within a predefined time interval. This hybrid approach provides the benefits of both event-triggered and time-triggered control, offering adaptability while ensuring periodic execution. To understand the behavior and characteristics of networked control systems under these triggering schemes, researchers have proposed various methodologies and modeling techniques. Switched system modeling methods have been employed to capture the uncertainty and time-varying nature of network-induced delays in event-triggered and self-triggered control schemes. Optimization techniques have also been used to design effective triggering strategies, enhancing the performance of networked control systems ([30] [71]). The development of triggering control schemes, including time-triggered, event-triggered, and self-triggered control, has significantly advanced Large-scale systems. These strategies aim to improve communication and control efficiencies and optimize resource utilization.

1.2 Our Contribution

In the realm of Large-Scale Systems, Networked Control Systems (NCSs) have emerged as a crucial field of study, enabling the control of complex interconnected systems. However, as we mentioned previously, the presence of network-induced delays and bandwidth limitation poses significant challenges to the stability and efficiency of these systems. the main contributions of this memoir are as follows:

• Obtain a maximum allowable network-induced delay bound guaranteeing the stability and stabilization of NCSs. We used the idea of addressing LSSs as a sampled-data multi-systems by constructing new LKFs including simple, double integral terms and also new augmented LKFs vector, and also used novel lemmas (Wirtinger and extended reciprocally lemmas) to estimate the LKFs vector derivatives we obtained the stability and control design conditions.

• Design a novel Event-Triggered Control (ETC) methodology that effectively mitigates network loads in LLSs and enhances the network quality of service.

• Developing a robust output feedback networked controller by incorporating the proposed event-triggered mechanism, which not only minimizes the number of transmitted packets but also enhances the system's resilience against external disturbances.

• Verify the Condition obtained on the special case of Large scale systems which is networked control system architecture and on the real Large-scale systems.

1.3 Thesis organization

The thesis is organized as follows:

Chapter 1 provides a general introduction to Large-Scale Systems (LSS) and their various control techniques, communication protocols, and the strategy of Event-Triggered Control (ETC). Subsequently, a section is presented that reviews the history and recent trends of LSS and ETC. Firstly, it discusses the development and architectures of LSS, followed by the advantages and disadvantages of using Distributed Control Systems (DCS) and Networked Control Systems (NCS) throughout history. Finally, we provide a review of one of the solutions proposed for these systems to reduce communication problems, namely the recent trends in triggered control. The contributions made within the framework of this thesis are then presented in the contribution section. Finally, this chapter concludes with the thesis organization section, which summarizes and facilitates the presentation of this work for readers.

Chapter 2 begins with an introduction that discusses the structures, modeling, and real protocols used in large-scale systems (LSSs), along with current research issues and future directions. The chapter explores the use of these strategies in industrial systems. Subsequently, a section is presented that discusses the components of an industrial LSS, including sensors, actuators, and control units. Next, we present the essential architecture of LSS and its structures: hierarchical, decentralized, and distributed structure. For each structure, we provide diagrams and explain their functioning. One of the most challenging problems in our control systems, which we address after presenting the structures, is the modeling of LSSs. We focus on continuous-time sampled data modeling with input and stochastic delay, as well as bandwidth limitation, as required by our specific problem. The following section comprises examples or brief representations of some real control systems in terms of LSSs. We examine the advantages and disadvantages of SCADA and DCS. Notably, we discuss the main characteristics of real communication protocols used in LSSs, such as industrial Ethernet with its types (EtherCAT, EtherNet/IP, CSMA/CD, and CSMA/CA), the HART protocol, and the Controller Area Network protocol. Consequently, we conclude that NCS is the most suitable choice for large-scale systems, offering greater manipulability compared to classic Distributed Control Systems (DCS). With NCSs, we have the flexibility to design and implement various control strategies tailored to our specific needs.

In Chapter 3, we focus on the Event-Triggered Control design of LSSs subject to network-induced delay and external disturbances. The chapter begins with an introduction to our work. Subsequently, we provide some preliminaries, including the system's general model and certain assumptions that assist us in our work. We also present the general scheme of the control loop we will work on, along with the state of all its components and the type of controller. Finally, we introduce the mathematical model and some lemmas. Moreover, stability analysis becomes our next focus. We employ the Lyapunov-Krasovskii Functional, in the proof of our theorem. This approach derives conditions based on Linear Matrix Inequalities (LMIs), which are necessary to address our proposed problem. It allows us to specify the system's maximum allowable delay bound, using Finsler's and extended reciprocally lemmas. Next, we present the second contribution of this thesis, which introduces a new design for the Event-Triggered Mechanism. To achieve this, we develop a co-design procedure that enables the simultaneous determination of trigger parameters and gains for the networked controller. Lastly, to demonstrate the effectiveness and superiority of our proposed NCS design methodology for LSSs, we provide three numerical examples. The primary goal of these examples is to reduce the number of unnecessary transmissions, thus conserving network bandwidth, while ensuring guaranteed closed-loop stability.

Chapter 2

Large-scale Systems: Architectures, Modeling, and Real Control protocols

2.1 Introduction

Industries today require efficient control systems as they become more complex as we mentioned previously. The development of industrial Large-Scale Systems (LSSs) has led to different types of control systems that integrate information from various domains. LSSs find applications in critical infrastructures like petrochemicals and electricity networks. However, they face challenges in estimation, control, structure identification, and cyber-physical security. This chapter provides an overview of LSS components such as sensors, controllers, actuators, communication protocols, and networks. It also explores hierarchical, decentralized, and distributed structures. Modeling and control of large-scale systems in continuous time, considering network-induced delay and bandwidth limitation, are discussed. Real control protocols like SCADA and DCS are mentioned, along with their advantages and disadvantages. Lastly, a real protocol used in large-scale systems is introduced. LSSs find applications in various domains, including industrial automation systems like Distributed Control Systems. These systems enable the modeling and control of complex systems with multiple interacting components, benefiting industrial automation settings by coordinating interdependent subsystems for optimized production efficiency. The current research issues and future directions of large scales are all about System Modeling and Event-Triggered Control.

2.2 Large-Scale Industrial systems components

2.2.1 Sensors: Sensors are devices that detect physical variables and convert them into measurable electrical signals. Temperature, pressure, flow, and level sensors are a few examples of the typical sensor types utilized in industrial control systems. The output of a sensor can be either analog or digital, and it can be continuous or discrete. In Large scales, sensors are often used to provide feedback to the controller, allowing it to make real-time adjustments to the system. The sensor in large-scale systems is a smart sensor that is able to sense, sample, and quantify the measurement signal before transmitting it through a communication network to the controller, this also means that the sensor plays an important role in networked systems [60] [24] [59].

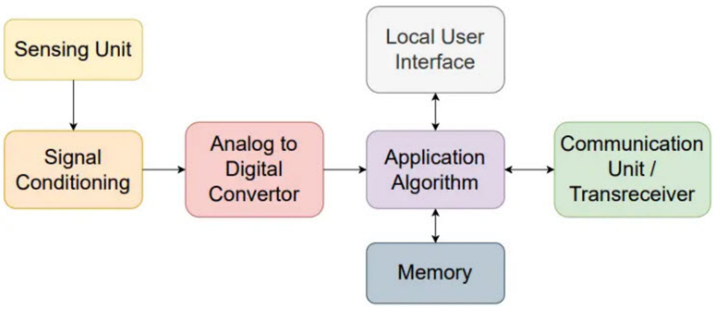

Figure 2.1: schematic Working of Smart Sensors.

2.2.2 Control Units: Control units are an essential tool that many large-scale industrial systems rely on to function safely and smoothly. the controller is an industrial control processor that has different software components responsible for monitoring and controlling industrial processes. These systems allow operators to set certain parameters for a process and then automatically adjust them as needed to keep the process within safe operating limits it compares the value or status of the process variable (PV) being controlled with the desired value or setpoint (SP) and applies the difference as a control signal to bring the process variable output of the plant to the same value as the setpoint. There are several dynamic controllers used in LLCs, like the PID controller, the state feedback controller, the output feedback controller, and the LQR controller. In LSSs the controller cannot process signals at the same moment which the sensor is sending the information due to the existence of different control node used the communication channel(congestion) where it needs waits its turn to transmit its signal, this lead to occur a delay in the reception of signals and maybe a loss or disordering in received signals. This phenomena induced by the network degrade the performance and maybe lead to instability of the networked control systems which implies solving these imperfections when designing the control system loops [61] [2] [14] [76].

2.2.3 Actuators:

Actuators are devices that convert energy into mechanical motion to move the system within its operational limits or safety states. Some common types of actuators used in industrial control systems include motors, valves, and hydraulic or pneumatic actuators. On large scales, the control signal for actuators is often provided by the ZOH, which converts the digital signal from the controller into an analog signal. The mathematical relationship between the input and output of an actuator is often defined by a transfer function or a mechanical model.

2.2.4 Communication Protocols and Networks:

Communication networks play a critical role in control systems these protocols assume a paramount position in enabling seamless and efficient functioning. They provide a means for transmitting control signals and feedback data between different components, such as sensors, actuators, and controllers. There are several types of communication networks used in industrial control systems, including Ethernet, CAN bus, and wireless networks. The choice of the network depends on various factors, such as the required data rate, the distance between components, and the level of interference in the environment.
For example, Ethernet is a popular choice for high-speed communication over long distances, while CAN bus is commonly used in automotive and industrial applications due to its robustness and low cost. Wireless networks, on the other hand, are suitable for applications where wired connections are not possible or practical. To design and analyze communication networks, engineers often use network models. These models help to understand the mathematical relationship between the input and output of a communication network, which is essential for optimizing network performance and ensuring reliable communication between components.

2.3 The different structures of Large-Scale systems

In LSSs sophisticated systems require precise and reliable control as we mentioned above, to ensure their safe and efficient operation. The control functions of these systems are organized into different structures each with its own advantages and disadvantages. In this part, we will introduce the different structures of large-scale systems and discuss their strengths and weaknesses. Here's a schema that represents the connection between subsystems before going through its different structures:

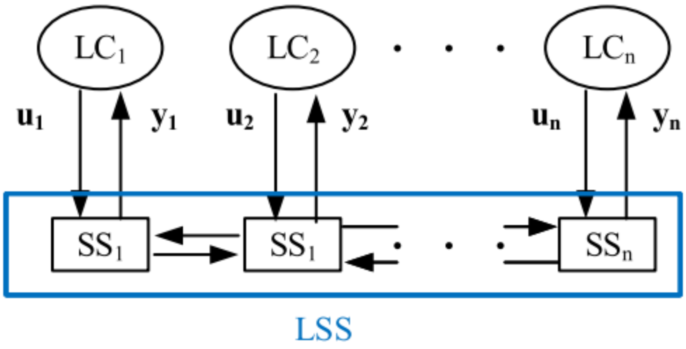

Figure 2.2: LSS, where each SS is controlled by a local controller LC. [26]

The structure of LSS refers to the way in which control tasks are distributed among the nodes. This distribution of tasks is critical to the overall performance and reliability of the system. Proper structuring ensures that each node performs its designated control task effectively and efficiently, while also communicating with other nodes as needed. By optimizing the distribution of control tasks in this way, networked systems can achieve their desired level of performance and responsiveness, making them an essential tool in modern automation and control applications.

2.3.1 Hierarchical structures

Also known as pyramid structures, is a commonly used control structure in large-scale industrial systems. This structure organizes control functions into multiple levels or layers, with each level responsible for a specific part or aspect of the system. This creates a clear chain of command and a top-down approach to decision-making. The higher levels of control in this structure are responsible for supervisory functions, while the lower levels are responsible for local control. This structure enables efficient and effective control of large-scale industrial systems by dividing control functions into manageable parts, optimizing system performance and efficiency. However, hierarchical control structures are typically only used in stable, less complex environments. This is because they can lead to slow decision-making, lack of communication between departments, and difficulty adapting to change. As such, other control structures may be more appropriate in more dynamic or complex environments. As a result, hierarchical control structures are an effective way to manage large-scale industrial systems, as long as they are used in the appropriate contexts and with an awareness of their limitations.

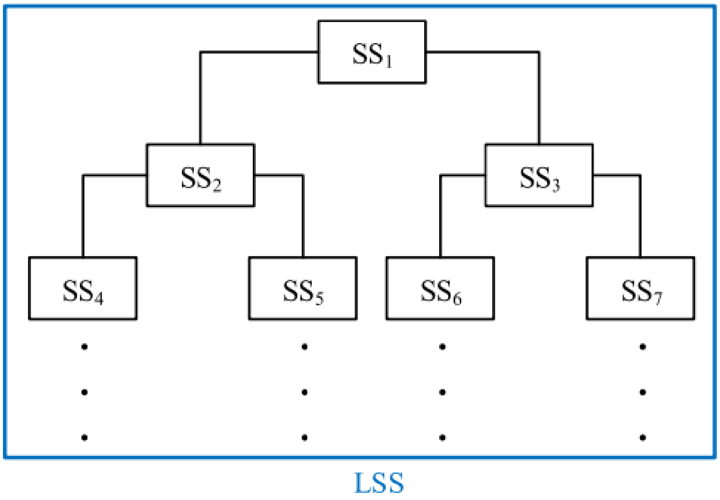

Figure 2.3: Hierarchical architecture of an LSS [26]

2.3.2 Decentralized structures

For more than three decades, the concept of decentralized structure control has garnered widespread popularity as an approach to efficiently manage large-scale systems. This innovative methodology has proven its efficacy in overcoming the challenges posed by dimensionality, uncertainty, and information structure constraints. In a decentralized system of this nature, paramount importance is placed on carefully considering the interconnections between individual subsystems. [6] [77]. This strategic consideration allows for the formulation of control laws that capitalize on locally available subsystem states or outputs, resulting in exceptional computational efficiency.

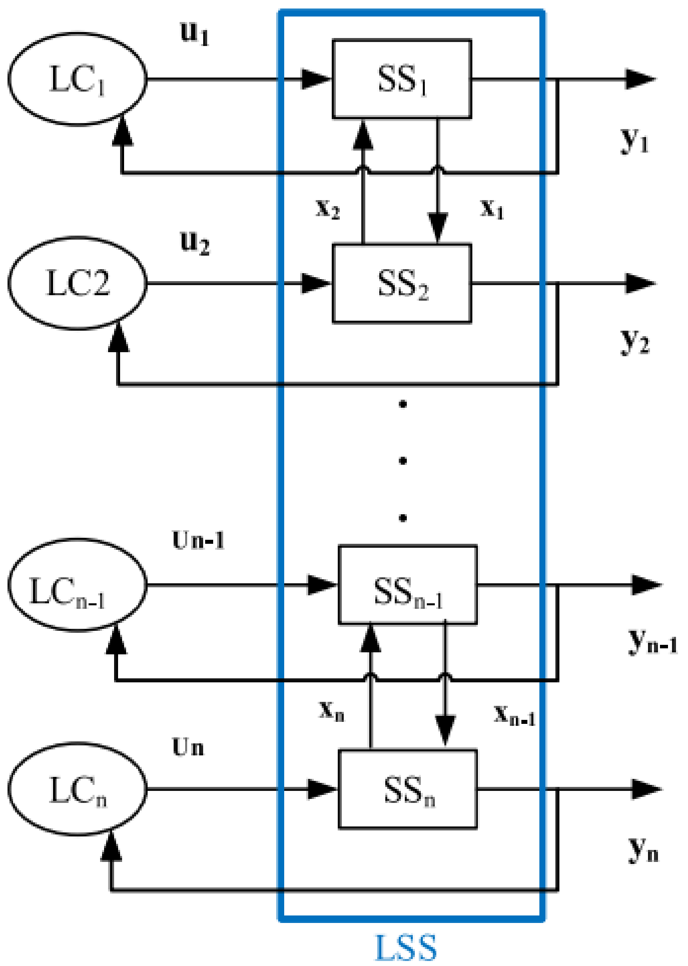

Figure 2.4: Decentralized controller with n SSs [26].

2.3.3 Distributed structures

Distributed control is a powerful control structure that distributes control functions across multiple devices, with each device responsible for a specific part of the system. This structure is particularly useful in complex systems where multiple subsystems need to communicate and coordinate with each other. By breaking down the control functions into smaller, more manageable parts, distributed control can increase system efficiency, reduce complexity, and improve reliability. Furthermore, this structure is highly scalable and can be easily expanded or modified as needed, making it an ideal choice for systems that require flexibility and adaptability. The decentralized control is the most common structure for LSSs, as it offers flexibility by allocating independent local controllers (LCs). This means that if one LC needs to be changed or redesigned due to a malfunction or fault, there is no need to redesign the other LCs. Distributed control involves multiple agents that communicate with each other to achieve a common goal. Each agent has its own controller and can make decisions based on local information and communication with neighboring agents. [52, 67].

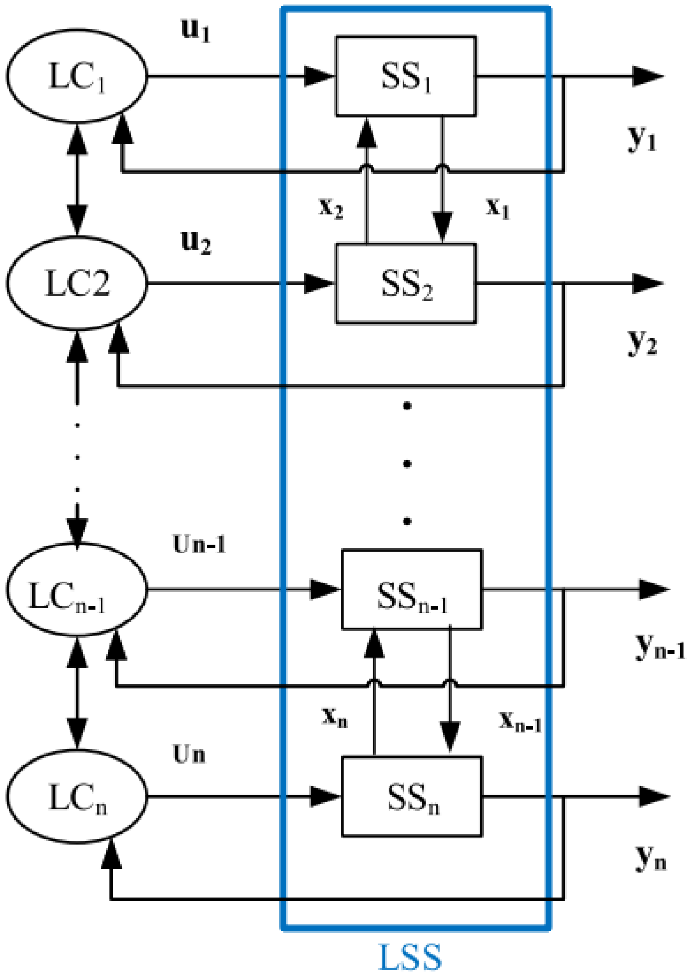

Figure 2.5: Distributed controller with n SSs [26].

2.4 Modeling of Large-Scale Systems

These systems are studied in the interdisciplinary research area of network and control theory and are becoming increasingly important in various industrial applications. In this section, we present the modeling of a large-scale system as a multi-sampled data system and model the network-induced delay and bandwidth limitation in such architecture.

2.4.1 Continuous-time sampled-data LSS

We present the LSS as a Continuous-time system where sensors, actuators, and controllers are interconnected by communication networks divided into subsystems, and the system operates continuously in time. Continuous-time large-scale models are used to represent systems where the state of a system changes continuously over time. These models are often represented by a set of coupled partial differential equations or ordinary differential equations to give a general sense of the type of systems considered, a linear time-invariant continuous LSS composed of N interconnected SSs is presented [[26], [13]]. The state-space representation of the i_{th} SS is formulated as follows:

$$\begin{cases} \dot{x}_i(t) = A_{ii}x_i(t) + B_{ii}u_i(t) + \sum_{\substack{j=1 \\ j\neq i}}^{N} A_{ij}x_j(t) + \sum_{\substack{j=1 \\ j\neq i}}^{N} B_{ij}u_j(t) \\ y_i(t) = C_{ii}x_i(t) + \sum_{\substack{j=1 \\ j\neq i}}^{N} C_{ij}x_j(t) \end{cases} \tag{2.1}$$

where $x_i(t) \in \mathbb{R}^{n_{xi}}$, $u_i(t) \in \mathbb{R}^{n_{ui}}$, and $y_i(t) \in \mathbb{R}^{n_{yi}}$ represent state, input, and output of ith SS, respectively. Moreover, A_{ii}, B_{ii}, and C_{ii} indicate the system, input, and output matrices of SSi, respectively. Besides, A_{ij}, B_{ij}, and C_{ij} denote interconnection matrices of system, input, and output matrices, respectively. If we collect all the SSs and represent them into one overall system, that system would be represented by the familiar linear state-space model of the overall LSS and is described as follows [26] [13]:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \tag{2.2}$$

For all the next: $x(t) = [x_1(t)\, x_2(t)\, \ldots\, x_{N-1}(t)\, x_N(t)]^T$, $u(t) = [u_1(t)\, u_2(t)\, \ldots\, u_{N-1}(t)\, u_N(t)]^T$, and $y(t) = [y_1(t)\, y_2(t)\, \ldots\, y_{N-1}(t)\, y_N(t)]^T$. and LSS composed of N interconnected SSs

$$A = \begin{bmatrix} A_{11} & A_{12} & \ldots & A_{1(N-1)} & A_{1(N)} \\ A_{21} & A_{22} & \ldots & A_{2(N-1)} & A_{2(N)} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ A_{(N-1)1} & A_{(N-1)2} & \ldots & A_{(N-1)(N-1)} & A_{(N-1)(N)} \\ A_{(N)1} & A_{(N)2} & \ldots & A_{(N)(N-1)} & A_{(N)(N)} \end{bmatrix}, B = \begin{bmatrix} B_{11} & B_{12} & \ldots & B_{1(N-1)} & B_{1(N)} \\ B_{21} & B_{22} & \ldots & B_{2(N-1)} & B_{2(N)} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ B_{(N-1)1} & B_{(N-1)2} & \ldots & B_{(N-1)(N-1)} & B_{(N-1)(N)} \\ B_{(N)1} & B_{(N)2} & \ldots & B_{(N)(N-1)} & B_{(N)(N)} \end{bmatrix}$$

$$C = \begin{bmatrix} C_{11} & C_{12} & \dots & C_{1(N-1)} & C_{1(N)} \\ C_{21} & C_{22} & \dots & C_{2(N-1)} & C_{2(N)} \\ \dots & \dots & \dots & \dots & \dots \\ C_{(N-1)1} & C_{(N-1)2} & \dots & C_{(N-1)(N-1)} & C_{(N-1)(N)} \\ C_{(N)1} & C_{(N)2} & \dots & C_{(N)(N-1)} & C_{(N)(N)} \end{bmatrix}$$

Where the system state evolves continuously over time and is influenced by network-induced time delays, packet dropouts, and other communication-related factors [1] [40]. Several techniques have been developed for the analysis and control of continuous-time LSSs, state feedback control is a technique that uses the full state of the system to determine the control input. Output feedback control, on the other hand, uses only the output of the system to determine the control input [28]. Furthermore, Event-triggered control is a type of control system that only sends control signals when specific triggering events occur, such as a change in the system's state [38]. Researchers have proposed various methods to deal with network-induced time delays and packet dropouts in continuous-time LSSs. Delay-dependent control is a type of control that considers the effects of time delays and tries to compensate for them by using information about the size and variation of the delay. Delay-independent control, on the other hand, assumes that the delay is constant and does not vary over time. Model predictive control also as we had mentioned before is a method that uses a model of the network to predict future system behavior and adapt control inputs accordingly [23].

2.4.1.1 Network-induced delay model in LSS Network-induced delay is an important factor to consider in the modeling and control of LSSs [74]. It refers to the delay that occurs when transmitting data over a communication network or protocol, which can cause instability and performance degradation in the control system. It has been observed that there are two types of time delays, the first being the delay from the sensor to the controller, which denotes the interval between sampling the signal from sensors and its reception by the controller, and the second being the delay from controller-to-actuator, which denotes the time between generating the control signal and its accessibility at the actuator. Generally, these delays are caused by various factors such as medium access delay, transportation delay, congestion delay, and other network-related factors [32]. To account for the network-induced delay in the control system, various approaches have been proposed, including the use of a discretization technique for continuous delay [61] [74], event-triggered control [16], and packet-based control.

An example of a continuous-time large-scale networked control system model that considers network-induced delay is presented in [74]. It offers an example of a continuous-time large-scale networked control system model that takes network-induced delay into account. It applies a discretization technique for the network-induced delay to expand the packet-based control approach to control systems to the continuous-time case. The method is applied to a system that consists of two subsystems and a communication network that connects them. The authors show that the proposed approach efficiently deals with network-induced delay and improves the control system's stability and performance [57]. The network-induced delay can be incorporated into the state-space model of the system as a delay term in the input-output relationship. Let's consider an example of a petrochemical plant where the process control system is distributed across multiple devices and connected through a communication network. So, the network-induced delay can lead to instability and poor performance of the control system. By incorporating the delay term in the state-space model of the system and using control techniques such as predictive control, the impact of the delay can be minimized and the system can be made more stable and responsive.

2.4.1.2 Input delay system approach In the input delay approach, the LSSs is modeled as a system with a time-varying delay where the time-varying delay includes the delay from the sensor-to-controller, the delay from controller-to-actuator, the computation delay, and the packets dropout represented as a delay. This approach was developed also to solve the synchronization problem of the complex network by considering signal sampling. The main and important issue in this approach is determining the maximum allowable upper bound (MAUB) of transmission delay which guarantees the stability and the good performance of LSSs. Also, the determination of the maximum allowable upper bound of transmission delay are important factor for practical applications Therefore, the NCSs closed-loop was described by the following time-varying system with input delay:

$$\begin{cases} \dot{x}_i(t) = A_{ii}x_i(t) + B_{ii}K_{ii}x_i(t-\tau(t)), \\ x(t) = \phi(t), \qquad \tau(t) \in [-\tau_M, -\tau_m)\,. \end{cases} \tag{2.3}$$

with

$$\begin{cases} 0 \leq \tau_m \leq \tau(t) \leq \tau_M \text{ or } (\tau_M + (\eta+1)h \text{ if packet dropout}), \\ \tau_m > 0, \tau_M > 0, \eta \geq 0. \end{cases} \tag{2.4}$$

where τ_m, τ_M, η are the upper value and lower value and number of packet loss, respectively. It is important to study network-induced delays in LSS models as these delays can degrade system performance and even destabilize the system. Simulation and modeling techniques have been employed to understand and estimate the effects of network-induced delays on system performance [29] [53].

2.4.1.3 Stochastic Delay The mutually independent stochastic delay model is often applied to the modeling and control of large systems with random delays when the probabilistic dependence is unknown [18] This imperfection combines constant and random delays and is characterized by a time-varying delay that follows a particular probability distribution. Using a state space model, the stochastic network-induced delay can be expressed as:

$$\tau(t) = \tau_1(t) + \tau_2(t)$$

where $\tau_1(t) = \sigma(t) \cdot \tau(t)$, $\tau_2(t) = (1 - \sigma(t)) \cdot \tau(t)$. and $\sigma(t)$ is a Bernoulli process that describes the delayed distribution. An example of a stochastic delay in a state space model is:

$$\begin{cases} \dot{x}(t) = Ax(t) + \sigma(t)BKx(t - \tau_1(t)) + (1 - \sigma(t))BKx(t - \tau_2(t)) \\ y(t) = Cx(t) + \sigma(t)DKx(t - \tau_1(t)) + (1 - \sigma(t))DKx(t - \tau_2(t)) \\ x(t) = \varphi(t), \quad \forall t \in [-\tau_{\max}, -\tau_{\min}] \end{cases}$$

Where $\tau(t)$ represents the stochastic network delay with upper limit τ_{max}, lower limit τ_{min}, and median τ_{med}, $\sigma(t)$ is a Bernoulli distribution representing the probability distribution of $\tau(t)$, and A, B, C, and D are system matrices.

2.4.1.4 Bandwith Limitation Any communication network has limited bandwidth which is the number of bits that can be transmitted per second, this limitation of the bandwidth depends not only on the physical bandwidth but also on the efficiency of encoding the data into packets, how efficiently the network operates in terms of inter-frame times (long or short), and whether network time is wasted due to message collisions. Which imposes significant constraints on the operation of LSSs.

For this purpose, the researchers made tremendous efforts in determining the minimum bit rate that is needed to achieve the control objectives, Among these research the involving of **Minimum bit rate** necessary to stabilize an LTI system has been derived, **Average bit rate** where is a measure of how infrequent feedback information is needed (in digital networks) to guarantee that the system remains stable, **Intermittent feedback** in which the open-loop is closed for certain fixed or time-varying periods, leading to opportunistic situations where the sensor sends bursts of information when the network is available, this helps in taxing the network less. **Quantified feedback** which is provided in the digital system implementation, and if the open-loop system is unstable, only then can we determine the minimum average bit rate to process feedback information. Further research on communication constrained feedback channels is establishing a connection between stabilizability and an inequality relating feedback channel data to open-loop eigenvalues.

2.5 The different real Large-scale systems

In the world of industrial automation, control systems play a pivotal role in guaranteeing the seamless and efficient operation of intricate processes. These control systems rely on various conditions, such as robust communication networks and reliable protocols, to ensure the smooth transmission of signals and critical information throughout the entire process. Any failure in this operation can significantly impact the stability and efficiency of the system, underscoring the crucial nature of these protocols. Consequently, it becomes imperative to explore some of these protocols in greater detail. Within large-scale industrial systems, multiple control models are employed, each exhibiting distinct strengths and weaknesses. These control models serve as the backbone of industrial automation, enabling optimized performance and effective management of complex industrial processes.

2.5.1 Supervisory Control And Data Acquisition:

SCADA is a system of software and hardware elements that allows industrial organizations to control industrial processes locally or at remote locations, monitor, gather, and process real-time data, and directly interact with devices such as sensors, valves, pumps, motors, and more through human-machine interface (HMI) software, and record events into a log file [17] SCADA systems are crucial for industrial organizations since they help to maintain efficiency, process data for smarter decisions, and communicate system issues to help mitigate downtime. The basic SCADA architecture begins with programmable logic controllers (PLCs) or remote terminal units (RTUs). PLCs and RTUs are microcomputers that communicate with an array of objects such as factory machines, HMIs, sensors, and end devices, and then route the information from those objects to computers with SCADA software. The SCADA software processes, distributes, and displays the data, helping operators and other employees analyze the data and make important decisions [44] Supervisory Control and Data Acquisition (SCADA) systems are widely used in various industries to monitor and control large-scale operations. These systems are essential for managing complex processes and ensuring the smooth operation of critical infrastructure1. Some of the key advantages of SCADA systems include centralized control, real-time data, improved efficiency, increased reliability, and remote access1. However, SCADA systems also have some disadvantages. They can be expensive to install and maintain, susceptible to cyber-attacks, and complex to use1.

2.5.1.1 Advantages of SCADA there are several advantages of SCADA among them: ***Large data storage capacity*** where SCADA systems have a massive storage capacity, allowing operators to keep track of and analyze loads of information over long periods. ***Flexibility*** where It can control large-scale processes that can include multiple sites and work over large distances as well as small distances.

2.5.1.2 Disadvantages of SCADA between them: ***Complexity:*** These systems can be complex and difficult to use, requiring specialized training and knowledge to operate effectively. ***Vulnerability to cyber attacks:*** It can be vulnerable to hacking and other forms of cybercrime, which can result in unauthorized access to sensitive data and the ability to control or manipulate industrial processes [51].

2.5.2 Distributed Control Systems

LSSs frequently employ DCS, actionnaly it's the same traditional structure a sort of real control paradigm. It is a decentralized control system that splits up the control duties among several controllers, enabling a system that is more adaptive and versatile. In process control applications, where several control loops are necessary to maintain the system's smooth functioning, DCS is especially well-suited. Many benefits of DCS include increased dependability, quicker reaction times, and more system flexibility.

2.5.2.1 Advantages of DCS there are several advantages of SCADA among them: ***Modular design*** where it allows for easy expansion and upgrades. This flexibility accommodates changing process control requirements, minimizing costs and disruptions to production while ensuring critical processes remain operational. ***Centralized monitoring*** that Centralized monitoring enables operators to swiftly detect and address system issues, identify trends, and integrate with other software for real-time data analysis, improving efficiency and system reliability.

2.5.2.2 Disadvantages of DCS Between them: ***Cost*** where its implementation can be costly, hindering small and medium-sized businesses. Specialized hardware, software, and skilled personnel are required. Training expenses add to the upfront costs. Despite the financial barriers, long-term benefits like improved control reduced downtime, and increased efficiency make DCS valuable in the end. ***Single point of failure*** where it relies on centralized control, but system failures can disrupt multiple processes, leading to downtime and lost productivity. A single point of failure can halt an entire plant or production line, posing safety risks. Maintenance and redundancy are crucial to minimizing downtime and production loss.

2.5.3 The different real protocols used in Large scale Systems

Large-scale systems are characterized by their extensive scale, intricate designs, and diverse components, which often introduce delays and modeling challenges. Among these complexities, communication protocols emerge as a critical factor, shaping the performance and differentiation of LSSs from alternative solutions. This subsection aims to provide a comprehensive understanding of the indispensable role played by communication protocols in LSSs, elucidating how they facilitate superior system responsiveness and efficiency. In the realm of Large-scale systems (LSSs), where large-scale systems operate with intricate designs and diverse components, the role of communication protocols cannot be underestimated. As we said previously these protocols assume a paramount position in enabling the seamless and efficient functioning of LSSs, distinguishing them from alternative solutions.

2.5.3.1 Industrial Ethernet IE refers to the utilization of Ethernet within industrial settings, employing specific protocols that ensure deterministic operations and real-time management. Notable Industrial Ethernet protocols encompass EtherCAT, EtherNet/IP, PROFINET, and Modbus TCP. By harnessing the capabilities of Ethernet, it empowers automation and control systems utilized in industrial manufacturing processes. The Ethernet has gained recognition for its affordability and ease of installation, making it a prevalent choice for industrial networks. However, it does come with a notable drawback—collisions between data nodes during transmission. When two nodes attempt to transmit simultaneously, a collision occurs, causing both nodes to wait for a random duration before re-transmission. To mitigate this issue, Ethernet commonly employs CSMA with the CD or CA mechanisms, which effectively prevent collision problems during communication. In industrial setups, three types of Ethernet are prominent: hub-based Ethernet switched Ethernet, and wireless Ethernet. The first type finds widespread implementation in office environments, while the second type is commonly utilized in manufacturing and control settings.

2.5.3.1.1 EtherCAT is a real-time Ethernet protocol that is commonly used in industrial automation applications. It is designed to provide high-speed communication and synchronization between devices in a networked control system. One of the key advantages of EtherCAT is its ability to synchronize devices with high accuracy and low latency. This is achieved through a unique "processing on the fly" approach, where each EtherCAT device reads data from the Ethernet frame(An Ethernet frame functions as a data unit within an Ethernet network, serving as a protocol data unit at the data link layer. It utilizes the transport mechanisms provided by the Ethernet physical layer. Essentially, an Ethernet frame acts as the payload carried by a data unit on an Ethernet link. Its size can range from 64 bytes to 1,518 bytes, depending on the data's transportation requirements.), processes it, and then sends it on to the next device in the chain. This allows for very fast communication times, with cycle times as low as a few microseconds. In addition to its high-speed communication and synchronization capabilities, EtherCAT also offers other features that make it well-suited for industrial automation applications. For example, it supports hot-plugging of devices, allowing new devices to be added to the network without disrupting the operation of existing devices. It also supports distributed clock synchronization, which enables all devices in the network to operate on a common time base.

2.5.3.1.2 EtherNet/IP EtherNet/IP (IP = Industrial Protocol) stands as an illustrious industrial network protocol renowned for seamlessly integrating the versatile CIP into the fabric of standard Ethernet. With its roots firmly planted in the United States, this dynamic and pervasive protocol has established itself as a frontrunner in the realm of industrial communications. Employed across a wide spectrum of industries, such as factory automation, hybrid manufacturing, and process control, EtherNet/IP has proven to be an indispensable force in empowering seamless connectivity and efficient data exchange within the industrial landscape. Building upon the robust foundations of the OSI model and the ubiquitous TCP/IP suite, EtherNet/IP triumphantly bridges the gap between traditional industrial automation systems and the world of Ethernet networking. With its ingeniously designed architecture, this protocol facilitates the seamless transmission of critical data, control commands, and real-time feedback across a myriad of industrial devices, making it a steadfast companion for industrial automation engineers and system integrators alike. Notably, EtherNet/IP embraces the principles of scalability and interoperability, allowing for seamless integration with a diverse range of devices, systems, and protocols within the industrial ecosystem. Whether it's connecting programmable logic controllers (PLCs), human-machine interfaces (HMIs), supervisory control and data acquisition (SCADA) systems, or even intelligent sensors, EtherNet/IP offers a versatile framework that harmonizes the various components of industrial infrastructure, fostering enhanced efficiency, flexibility, and ease of implementation. As a testament to its widespread adoption, EtherNet/IP has become deeply entrenched in the fabric of the American industrial landscape, empowering countless manufacturing facilities, assembly lines, and process plants to operate with unwavering precision and reliability. This protocol's enduring popularity can be attributed to its ability to cater to the diverse requirements of different industries, be it discrete manufacturing, continuous process control, or hybrid environments that blend the two.

2.5.3.1.3 Hub-Based Ethernet CSMA/CD Ethernet commonly employs Carrier Sense Multiple Access with Collision Detection (CSMA/CD) which is a (MAC) protocol used in Local Area Networking. It uses early Ethernet technology to overcome collision when it occurs. The approach effectively arranges the transfer of information by governing the exchange within a network that utilizes a common transmission medium. In this system, each device connected to the hub listens for network activity before transmitting data. This process is known as carrier sense. If the network is idle, the device can transmit its data without interference. However, if multiple devices attempt to transmit simultaneously, a collision occurs. When a collision is detected, the colliding devices cease transmission and wait for a random backoff time before reattempting. The random backoff time reduces the likelihood of another collision. The devices also send a jamming signal to alert other devices of the collision. This collision detection mechanism ensures fair access to the network and reduces data loss. A hub, also known as a multiport repeater, is a central connecting device that receives data from one port and forwards it to all other ports. As a hub operates at the physical layer of the network, it is unaware of the content of the data being transmitted. Therefore, it does not perform any filtering or routing. The Ethernet (CSMA/CD) frame format is crucial for successful data delivery over a network. Its key components include the preamble(7-byte field (56 bits) that serves as a synchronization sequence), SFD(1-byte field (8 bits), destination (6-byte field (48 bits) specifies the MAC) and source addresses (6-byte field (48 bits) that contains the MAC address), EtherType/Length(2-byte field (16 bits)), data(Its length can vary from 46 to 1500 bytes), and FCS(4-byte field (32 bits) that contains an error-detection code). The preamble synchronizes clocks and marks the start of a frame, while the SFD differentiates it from the preamble. The destination address identifies the recipient device, and the source address indicates the sender's device. The EtherType/Length field determines either the length of the data or the encapsulated protocol type. The data field carries the actual payload, and the FCS enables error detection using a CRC. This standardized format ensures reliable communication in shared Ethernet networks. However, hub-based Ethernet networks have limitations. As the network grows, collisions become more frequent, leading to decreased efficiency. Additionally, the shared medium introduces a single point of failure, as a fault in the hub can disrupt the entire network.

2.5.3.1.4 Switched Ethernet CSMA/CA Switched Ethernet uses full-duplex links where there's no way a collision can happen. CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) is a network multiple access method in which carrier sensing is used, in order to prevent interference, nodes make an effort to commence transmitting data only when they detect that the communication channel is not in use. The switched Ethernet protocol utilizes switch devices to establish connections between components in a Networked Control System. This approach effectively prevents collisions, enhances determinism, and improves overall network efficiency. Contrasting with hub Ethernet protocol, the key distinction lies in the intelligent handling of packet forwarding. Hubs transfer incoming traffic from any port to all other ports, resulting in collisions, while switches learn the network's topology and exclusively forward packets to the destination port. For instance, in a network, nodes connect to the switch via individual cables, eliminating collisions on any network cable. Switches employ either the cut-through or store-and-forward technique to transmit packets between ports. Cut-through involves reading the MAC address first and forwarding the packet accordingly, while store-and-forward verifies the complete packet using cyclic redundancy check (CRC) to ensure accurate transmission. Errors during verification lead to packet loss. Although switched Ethernet successfully avoids message collisions, it introduces a new challenge to NCSs: congestion within switches when one port receives an influx of packets from other ports, causing buffer congestion and delays. One way to address this issue is by implementing queueing principles such as First-In-First-Out (FIFO). This approach is simple and fair, but may not guarantee the quality of service (QoS) during heavy network traffic. Also, the priority queueing scheme is a preferred method where the network manager examines select data frames to determine their relative importance. This enables the classification of packets into different levels of queues based on their significance. Another approach, known as the per-flow queue, assigns queues different levels of priority or weights. These queues are then processed one by one in accordance with their priority. Higher-priority queues generally exhibit superior performance and may potentially impede lower-priority queues. By employing the priority queueing scheme, network managers gain valuable insights by analyzing specific data frames, allowing for the effective categorization of packets into distinct queues. Similarly, the per-flow queue method enables the assignment of varying levels of priority to queues, facilitating sequential processing based on priority. Higher-priority queues exhibit enhanced performance, potentially leading to the temporary blocking of lower-priority queues.

2.5.3.1.5 Wireless Ethernet CSMA/CA It's a sophisticated and efficient network multiple access method that empowers seamless communication in a multitude of interconnected devices. However, CSMA/CA takes it a step further, employing a remarkable collision avoidance mechanism that ensures nodes commence their transmissions only when the channel is unequivocally perceived as "idle." This distinctive attribute of CSMA/CA renders it particularly indispensable in the realm of wireless networks, where the deployment of the conventional collision detection counterpart, CSMA/CD, is rendered infeasible due to the nature of wireless transmitters disabling their receivers during packet transmission. CSMA/CA operates at the Medium Access Control (MAC) layer and utilizes the frame format defined by the underlying wireless network technology, such as IEEE 802.11 (Wi-Fi). The frame format in CSMA/CA networks, like Wi-Fi, consists of essential components: Frame Control, Duration/ID, Receiver Address, Transmitter Address, Other MAC addresses, Sequence Control, Frame Body, and Frame Check Sequence (FCS). These components provide control, addressing, sequencing, and error detection functionalities. The frame format varies depending on the wireless network standard used, with additional fields in Wi-Fi networks, such as SSID and QoS control. CSMA/CA uses this frame format to manage wireless medium access and prevent collisions in shared environments. In wireless environments, CSMA/CA seamlessly orchestrates the division of the channel's bandwidth among multiple transmitting nodes within the collision domain, creating a harmonious coexistence and significantly reducing the likelihood of detrimental collisions. In its operational essence, CSMA/CA employs a thoughtful and meticulous process. Prior to initiating a transmission, each node conscientiously listens to the shared medium, remaining astutely vigilant for any discernible wireless signals. This vigilant monitoring allows the node to ascertain whether another node is currently transmitting, thus effectively averting collisions before they can occur. By observing the channel's "idle" periods and employing a proactive approach to access, CSMA/CA optimizes network efficiency, enabling seamless communication among interconnected devices and fostering a vibrant ecosystem of synchronized data exchange.

2.5.3.2 Highway Addressable Remote Transducer (HART) Presenting the revolutionary HART (Highway Addressable Remote Transducer) Protocol, an innovative blend of analog and digital open protocol specifically designed for industrial automation. This revolutionary protocol has become the cornerstone of process and instrumentation systems, catering to a wide range of applications, from basic automation projects to intricate industrial operations. Originally created by Emerson in the 1980s, HART emerged as a transformative solution that overcame the limitations of the traditional 4-20mA communication protocol. Unlike its predecessor, HART enables two-way communication, surpassing the constraints of transmitting only a single parameter or measured value. The brilliance of HART lies in its seamless integration of digital signals into analog signals, ensuring smooth and uninterrupted transmission while preserving the existing infrastructure. In HART, where innovation meets reliability, resulting in unparalleled capabilities for industrial automation.

2.5.3.3 Controller Area Network From Automotive Origins to Universal Applicability, CAN was initially developed by leading automotive manufacturers seeking a reliable and efficient communication system for their vehicles it defines the data link and physical layer of the Open Systems Interconnection (OSI) model. However, its potential quickly transcended the automotive industry, and today, it finds application in diverse fields such as industrial automation, aerospace, and more. This simplifying Complex Communication operates on a simple yet robust principle due to the fact that it uses a multi-master bus, where all messages are broadcast on the entire network using a differential signal with two logic states, called recessive and dominant. Enhancing efficiency, safety, and reliability One of the most significant advantages of CAN is its ability to enable efficient and reliable communication between devices its applications are virtually limitless as we said previously, from self-driving cars and smart homes to advanced medical equipment and space exploration. This universal applicability, simplified design, and remarkable benefits have made it an indispensable technology in our networked and LSSs [33].

2.6 Conclusion

After extensive research and diligent efforts undertaken throughout this chapter, LSSs are a wide field of control systems so we tried to present the major components and the different real structures with their benefits and disadvantages. Next, we focused on a very important part of this thesis concerning the modeling of continuous-time LSSs with network imperfections, and finally, we introduced some Protocols used in the implementation of networks on large scales with their characteristics, advantages, and inconveniences. In conclusion, we want to say that Networked Control Systems (NCSs) emerge as the most suitable and optimal choice for managing large-scale systems, surpassing the capabilities of conventional Distributed Control Systems (DCS) by offering enhanced manipulability and control.

Chapter 3

Event-triggered Control Design of Large-Scale Systems Subject to Network-induced Delay and External Disturbances

3.1 Introduction

The analysis of system stability plays a fundamental role in the field of control systems, especially when examining system behavior and designing controllers. The primary focus of this chapter is on the Lyapunov-Krasovskii functional (LKF). This approach involves carefully selecting LKFs that incorporate maximum information regarding network-induced imperfections. Therefore, we aim to determine the maximum allowable upper delay and utilize the stability analysis phase to derive LMI-based conditions that facilitate the design of the event-triggered mechanism. The subsequent sections of this chapter provide further explanations of the employed stability analysis methods. Furthermore, a co-design procedure is developed to obtain both trigger parameters and the gains of the proposed networked controller. We propose a new Event-Triggered Mechanism (ETM) to mitigate the network loads in NCSs. This is achieved through the design of a new stabilizing output feedback networked controller, which improves the robustness against external disturbances in the designed closed-loop NCS. The proposed NCS design methodology for LSSs is illustrated and compared to previous related results using an academic system and the benchmark model of power systems in simulation.

Finally, three numerical examples are presented to demonstrate the effectiveness and improvement of the proposed design procedure.

Notations 3.1 *In the next, * in matrices denote bloc transpose quantities, and + in matrices denotes matrix M–P inverse. For a matrix M of appropriate dimension, one denotes $\mathcal{H}(M) = M + M^T$. For diagonal matrix $A = diag(a_1, a_2) = \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix}$. A finite set of r positive integers is denoted $\mathcal{I}_r = \{1, ..., r\}$. Also, $\forall j \in \mathcal{I}_7$, the block entry matrices is expressed by $e_j = \begin{bmatrix} 0_{n\times(j-1)n} & I_{n\times n} & 0_{n\times(7n-j)n} \end{bmatrix}^T \in \mathbb{R}^{7n\times n}$, for example: $e_4 = \begin{bmatrix} 0 & 0 & 0 & I & 0 & 0 & 0 \end{bmatrix}^T$.*

3.2 Preliminaries

Let us consider the class of continuous-time linear systems described by the following state space representation:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + B_w\omega(t) \\ y(t) = Cx(t) \end{cases} \tag{3.1}$$

Where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$, $y(t) \in \mathbb{R}^q$ are respectively the system state vector, the control input vector, the output vector and $\omega(t) \in \mathbb{R}^p$ denotes the external disturbance which is assumed to belong to $L_2[0, \infty)]$, A, B, C and B_w are real constant matrices with appropriate dimensions.

In this work, the control loop is closed via a communication network, as is depicted in Fig.3.1. To mitigate the transmissions of data through the network and so saving its bandwidth, we propose, for the event generator, an improved dynamic ETM to decide whether the current sampling state measurements should be transmitted or not to the controller over the network.

Assumption 1 *The sensors are clock-driven with a fixed sampling period h and the controller and actuators are event-driven from an ETM implemented in the event generator.*

Suppose that the sensor is time-triggered with a fixed sampling period h and its sampling sequence is described by the set $\mathcal{S} = \{0, s_1, s_2, \ldots, s_k\}$, $s_k = kh$, $k \in \mathbb{N}$. By collecting these sampling data, the sample data $x(s_k)$ which beyond the designed triggering condition should be transmitted. We denote the event-triggered sequence as the set $\mathcal{T} = \{0, t_1, t_2, \ldots, t_k\}$, with $\mathcal{T} \subset \mathcal{S}$. So, the actuators will implement their control actions with these successfully transmitted output-based triggered data.

When sampled data is released by the event generator to the controller, it occurs a sensor-to-controller communication delay τ_k^{sc}, and controller-to-actuator communication delay τ_k^{ca}. The

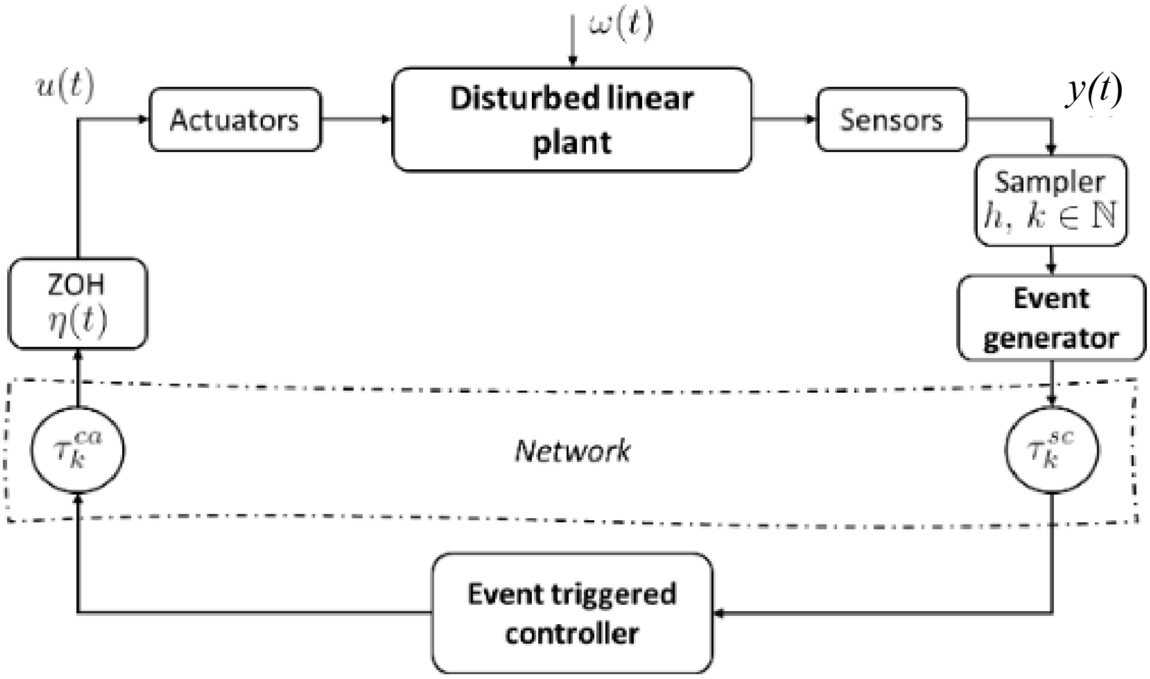

Figure 3.1: Networked control system scheme under ETM.

total network-induced delay can be lumped together as $\tau_k = \tau_k^{sc} + \tau_k^{ca}$ and satisfy $\tau_m \leq \tau_k \leq \tau_M$. To mitigate the transmissions of data through the network and so saving its bandwidth, we propose, for the event generator, a new ETM. That is to say, to decide whether the current sampling state measurements should be transmitted or not to the controller over the network, the next transmission instant t_{k+1} satisfies:

$$t_{k+1} = t_k + \min_{l \in N} lh | e_k^T(t) \Omega e_k(t) > \rho y^T(t_k) \Omega y(t_k) \tag{3.2}$$

where $\rho \in [0, 1]$, is given event-triggered thresholds and $\Omega > 0$ is an event-triggering weighting matrix to be designed. $e_k(t) = y(t_k) - y(t_k + lh)$ is the actual output error between the latest transmitting data and current real-time sampling data.

By considering the effect of the network transmission delay, the control signal is constant during the interval $\mathbb{I}_z = [t_k + \tau_k, t_{k+1} + \tau_{k+1})$, which can be divided, similarly the way borrowed in [68], into several sub-intervals such that $\mathbb{I}_z = \bigcup_{l=0}^{\bar{\upsilon}} \mathbb{I}_l$ with:

$$\mathbb{I}_z = \begin{cases} \mathbb{I}_{l=0} = [t_k + \tau_k, t_k + h + \tau_k), \ l = 0 \\ \mathbb{I}_l = [t_k + lh + \bar{\tau}, t_k + lh + h + \bar{\tau}), \ l = 1, 2, \ldots, \bar{\upsilon} - 1 \\ \mathbb{I}_{l=\bar{\upsilon}} = [t_k + \bar{\upsilon}h + \bar{\tau}, t_{k+1} + \tau_{k+1}), \ l = \bar{\upsilon} \end{cases} \tag{3.3}$$

Then, the delay version of the system can be constructed for every two successfully transmitted instants by defining $\eta(t) = t - (t_k + lh)$. Obviously, $\eta(t)$ is a piece-wise function with the assumption that

$$\eta_m = \tau_m \leq \eta(t) \leq \eta_M = \tau_M + h \tag{3.4}$$

with η_m, η_M are the minimum and maximum value of system delay $\eta(t)$. Corresponding to the proposed ETM, the controller low is defined as

$$u(t) = Ky(t_k) \tag{3.5}$$

From the definition of $\eta(t)$ and the state errors $e_k(t)$ we can write $y(t_k) = Cx(t - \eta(t)) + e_k(t)$ and the controller low becomes:

$$u(t) = K(Cx(t - \eta(t)) + e_k(t)) \tag{3.6}$$

Substituting (3.6) into (3.1), yields the expression of the closed-loop dynamics:

$$\begin{cases} \dot{x}(t) = Ax(t) + BK(Cx(t - \eta(t)) + e_k(t)) + B_w\omega(t) \\ y(t) = Cx(t) \end{cases} \tag{3.7}$$

To conclude these preliminaries, the purpose of this work is to provide LMI-based control design conditions (design of the gain matrix K) and the event-triggered generator parameters (design of the matrix Ω in (3.2)) such that, without external disturbances ($\omega(t) = 0$), the closed-loop dynamics (3.7) is asymptotically stable and, when $\omega(t) \neq 0$, the transfer of the external disturbances to the system's outputs is minimized such that the following H_∞ criterion is satisfied:

$$\int_0^\infty \left(y^T(s)y(s) - \gamma^2\omega^T(s)\omega(s)\right) ds < 0 \tag{3.8}$$

where the scalar $\gamma > 0$ denotes the disturbance attenuation level (performance index) to be minimized.

Problem statement. Provide LMI-based design conditions for the gain matrix K and the ETM weighting matrices Ω_1 and Ω_2, such that the closed-loop NCS (3.7) is Globally Asymptotically Stable (GAS) and resilient to deception attacks under Assumption.

Lemma 1 *[8] Let $\xi \in \mathbb{R}^n$, $G \in \mathbb{R}^{m \times n}$ and $Q = Q^T \in \mathbb{R}^{n \times n}$ such that $rank(G) < n$. Then, $\xi^T Q \xi < 0$,*

$\forall \xi \in \{\xi \in \mathbb{R}^n : \xi \neq 0, G\xi = 0\}$, *iff:*

$$\exists T \in \mathbb{R}^{n\times m} : Q + \mathcal{H}(TG) \prec 0 \tag{3.9}$$

Lemma 2 *(Extended Jensen's Inequality [35]) For any constant matrix* $\begin{bmatrix} Q & S \\ * & Q \end{bmatrix} > 0$*, a positive scalar* $\bar{\tau}$ *satisfying* $0 < \tau(t) < \bar{\tau}$ *and vector function* $\dot{x} : [-\bar{\tau}, 0] \to \mathbb{R}^n$ *such that the concerned integrals are well defined, we have:*

$$\begin{aligned} &-\bar{\tau}\int_{t-\bar{\tau}}^{t} \dot{x}^T(s)Q\dot{x}(s)ds \\ &\leq \begin{bmatrix} x(t) - x(t-\tau(t)) \\ x(t-\tau(t)) - x(t-\bar{\tau}) \end{bmatrix}^T \begin{bmatrix} Q & S \\ * & Q \end{bmatrix} \begin{bmatrix} x(t) - x(t-\tau(t)) \\ x(t-\tau(t)) - x(t-\bar{\tau}) \end{bmatrix} \end{aligned}$$

3.3 Main result

The main contribution of this paper is to propose an LMI-based procedure for the design of event-triggered controller (3.6) for NCS subject to network-induced delay and external disturbances, in order to reduce the network traffic by reducing the number of redundant released packets. The following theorem summarizes the proposed conditions.

3.3.1 Stability Analysis

Theorem 3.1 *For given constant scalars* $\eta_m > 0, \eta_M > 0$, $\rho > 0$, $\varepsilon_1 \geq 0$ *and* $\varepsilon_2 \geq 0$*, the closed-loop disturbed NCS* (3.7) *is robustly stabilized by the networked controller* (3.6)*, under the release instants defined by the ETM condition* (3.2)*, with a* H_∞ *disturbance attenuation level* $\gamma > 0$*, if there exist the real matrices* $\mathcal{P} > 0$, $Q_1 > 0$, $Q_2 > 0$, $R_1 > 0$, $R_2 > 0$, $\mathcal{N}_1 > 0$, $N_2 > 0$, $\mho > 0$, S, $\mathcal{M}$ *and* K *such that the following LMIs are satisfied:*

$$\begin{bmatrix} R_2 & S \\ * & R_2 \end{bmatrix} > 0 \tag{3.10}$$

$$\Phi_1 + \Phi_2 + \Phi_3^1 + \Xi + \mathcal{H}(\mathcal{M}\mathcal{G}) < 0 \tag{3.11}$$

$$\Phi_1 + \Phi_2 + \Phi_3^2 + \Xi + \mathcal{H}(\mathcal{M}\mathcal{G}) < 0 \tag{3.12}$$

With:

$$\mathcal{G} = \begin{bmatrix} A & 0 & BK & 0 & -I & B_w & BK \end{bmatrix}.$$

$$\Phi_1 = \begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ * & P_{22} & P_{23} \\ * & * & P_{33} \end{bmatrix} \begin{bmatrix} e_5 \\ 0 \\ e_5 \end{bmatrix}$$

$$\Phi_2 = e_1(Q_1 + Q_2 - R_1)e_1^T - e_2(R_1 + Q_1)e_2^T - e_4 Q_2 e_4^T + e_1 R_1 e_2^T + e_2 R_1^T e_1^T + e_5 \left(\eta_m^2 R_1 + (\eta_M - \eta_m)^2 R_2\right) e_5^T$$
$$+ \begin{bmatrix} e_2^T \\ e_3^T \\ e_4^T \end{bmatrix}^T \begin{bmatrix} -R_2 & R_2 - S & S \\ * & -2R_2 + \mathcal{H}(S) & R_2 - S \\ * & * & -R_2 \end{bmatrix} \begin{bmatrix} e_2 \\ e_3 \\ e_4 \end{bmatrix}$$

$$\Phi_3^1 = -\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} N_{11} & N_{12} & N_{13} \\ * & N_{22} & N_{23} \\ * & * & N_{33} \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \\ e_1 - e_3 \end{bmatrix} + (\eta_M - \eta_m)\mathcal{H}\Big(\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} N_{11} & N_{12} & N_{13} \\ * & N_{22} & N_{23} \\ * & * & N_{33} \end{bmatrix} \begin{bmatrix} e_5 \\ 0 \\ e_5 \end{bmatrix}$$
$$+ e_5^T(t) N_2 e_5 \Big) + \frac{1}{\eta_m} \begin{bmatrix} e_1^T \\ e_3^T \end{bmatrix}^T \begin{bmatrix} -N_2 & N_2 \\ * & -N_2 \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \end{bmatrix}$$

$$\Phi_3^2 = -\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} N_{11} & N_{12} & N_{13} \\ * & N_{22} & N_{23} \\ * & * & N_{33} \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \\ e_1 - e_3 \end{bmatrix} + \frac{1}{\eta_M} \begin{bmatrix} e_1^T \\ e_3^T \end{bmatrix}^T \begin{bmatrix} -N_2 & N_2 \\ * & -N_2 \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \end{bmatrix},$$

$$\Xi = -e_7^T \mho e_7 + e_1^T C_i^T C_i e_1 - \gamma^2 e_6^T e_6 + \rho(Ce_3 + e_7)^T C^{+T} \mho C^{+}(Ce_3 + e_7)$$

Proof 3.1 *Let us consider the following delay-dependent LKF candidate:*

$$V(t) = V_1(t) + V_2(t) + V_3(t) \tag{3.13}$$

where

$$V_1(t) = \theta^T(t)\mathcal{P}\theta(t)$$

$$V_2(t) = \int_{t-\eta_M}^{t} x^T(s) Q_1 x(s) ds + \int_{t-\eta(t)}^{t} x^T(s) Q_2 x(s) ds + \eta_m \int_{-\eta_m}^{0} \int_{t+\theta}^{t} \dot{x}^T(s) R_1 \dot{x}(s) ds d\theta$$
$$+ (\eta_M - \eta_m) \int_{-\eta_M}^{-\eta_m} \int_{t+\theta}^{t} \dot{x}^T(s) R_2 \dot{x}(s) ds d\theta$$

$$V_3(t) = (\eta_M - \eta(t)) \left(\theta^T(t) \mathcal{N}_1 \theta(t) + \int_{t-\eta(t)}^{t} \dot{x}^T(s) N_2 \dot{x}(s) ds \right)$$

with

$$\theta^T(t) = \begin{bmatrix} x^T(t) & x^T(t-\eta(t)) & \int_{t-\eta(t)}^{t} \dot{x}^T(t) \end{bmatrix}.$$

The LKF candidate (3.13) is positive if $\mathcal{P}$, $\mathcal{N}_1$, Q_1, Q_2, R_1, R_2 and N_2 are all positive definite matrices. In this case, the closed-loop system under METC (3.7) *is asymptotically stable if:*

$$\dot{V}(t) = \dot{V}_1(t) + \dot{V}_2(t) + \dot{V}_3(t) < 0 \tag{3.14}$$

Taking the derivative of $V_1(t)$ yields:

$$\dot{V}_1(t) = 2\theta^T(t)\mathcal{P}\dot{\theta}(t) \tag{3.15}$$

with $\dot{\theta}(t) = \begin{bmatrix} \dot{x}^T(t) & 0 & \dot{x}^T(t) \end{bmatrix}$*, Then, the equation* (3.15) *can be re-writing as:*

$$\dot{V}_1(t) = \zeta^T(t)\Phi_1\zeta(t) \tag{3.16}$$

With $\Phi_1 = \begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ * & P_{22} & P_{23} \\ * & * & P_{33} \end{bmatrix} \begin{bmatrix} e_5 \\ 0 \\ e_5 \end{bmatrix}$ *and*

$$\zeta(t) = \begin{bmatrix} x^T(t) & x^T(t-\eta_m) & x^T(t-\eta(t)) & x^T(t-\eta_M) & \dot{x}^T(t) & \omega^T(t) & (C^+e_k)^T(t) \end{bmatrix}^T.$$

Next, taking the derivative of $V_2(t)$, we obtain:

$$\begin{aligned} \dot{V}_2(t) = & x^T(t)(Q_1+Q_2)x(t) - x^T(t-\eta_M)Q_1x(t-\eta_M) + \dot{x}^T(t)(\eta_m^2R_1 + (\eta_M-\eta_m)^2R_2)\dot{x}(t) \\ & - \eta_m \int_{t-\eta_m}^{t} \dot{x}^T(s)R_1\dot{x}(t)ds - (\eta_M-\eta_m)\int_{t-\eta_M}^{t-\eta_m} \dot{x}^T(s)R_1\dot{x}(t)ds \end{aligned} \tag{3.17}$$

Applying the extended Jensen's inequality [35], we can write:

$$-\eta_m \int_{t-\eta_m}^{t} \dot{x}^T(s)R_1\dot{x}(s)ds \leq \begin{bmatrix} x(t) \\ x(t-\eta_m) \end{bmatrix}^T \begin{bmatrix} -R_1 & R_1 \\ * & -R_1 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\eta_m) \end{bmatrix} \tag{3.18}$$

Providing that $\begin{bmatrix} R_2 & S \\ * & R_2 \end{bmatrix} > 0$ *is satisfied, it yields:*

$$(\eta_M - \eta_m)\int_{t-\eta_M}^{t-\eta_m} \dot{x}^T(s)R_2\dot{x}(s)ds \leq \begin{bmatrix} x(t-\eta_m) \\ x(t-\eta(t)) \\ x(t-\eta_M) \end{bmatrix}^T \begin{bmatrix} -R_2 & R_2-S & S \\ * & -2R_2+H(S) & R_2-S \\ * & * & -R_2 \end{bmatrix} \begin{bmatrix} x(t-\eta_m) \\ x(t-\eta(t)) \\ x(t-\eta_M) \end{bmatrix} \tag{3.19}$$

Then, the equation (3.17) *can be re-writing as:*

$$\dot{V}_2(t) = \zeta^T(t)\Phi_2\zeta(t) \tag{3.20}$$

With $\Phi_2 = e_1(Q_1+Q_2-R_1)e_1^T - e_2(R_1+Q_1)e_2^T - e_4Q_2e_4^T + e_1R_1e_2^T + e_2\tilde{R}_1^Te_1^T + e_5(\eta^2R_1+(\eta-\bar{\eta})^2R_2)e_5^T$
$+ \begin{bmatrix} e_2^T \\ e_3^T \\ e_4^T \end{bmatrix}^T \begin{bmatrix} -R_2 & R_2 - S & S \\ * & -2R_2 + \mathcal{H}(S) & R_2 - S \\ * & * & -R_2 \end{bmatrix} \begin{bmatrix} e_2^T \\ e_3^T \\ e_4^T \end{bmatrix}.$

Now, taking the derivative of $V_3(t)$*, one can obtain:*

$$\begin{aligned} \dot{V}_3(t) = &-\left(\theta^T(t)\mathcal{N}_1\theta(t) + \int_{t-\eta(t)}^{t} \dot{x}^T(s)N_2\dot{x}(s)dsd\lambda\right) \\ &+ (\eta_M - \eta(t))\left(2\theta^T(t)\mathcal{N}_1\dot{\theta}(t) + \dot{x}^T(t)N_2\dot{x}(t)\right) \end{aligned} \tag{3.21}$$

Applying Jensen's inequality on the integral terms, the equation 3.21 can be bounded as ;

$$\dot{V}_3(t) \leq (\eta_M - \eta(t))\left(2\theta^T(t)\mathcal{N}_1\dot{\theta}(t) + \dot{x}^T(t)N_2\dot{x}(t)\right) - \left(\theta^T(t)\mathcal{N}_1\theta(t) - \frac{1}{\eta(t)}\begin{bmatrix} x(t) \\ x(t-\eta(t)) \end{bmatrix}^T \begin{bmatrix} -N_2 & N_2 \\ * & -N_2 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\eta(t)) \end{bmatrix}\right). \tag{3.22}$$

Therefore, according to (3.15), (3.16) *and* (3.22) *the inequality* (3.14) *can be writing as:*

$$\dot{V}(t) \leq \zeta^T(t)\Big(\Phi_1 + \Phi_2 + \Phi_3(\eta(t))\Big)\zeta(t) < 0 \tag{3.23}$$

$$\dot{V}_3(t) = \zeta^T(t)\Phi_3(\eta(t))\zeta(t) \tag{3.24}$$

With

$$\Phi_3(\eta(t)) = -\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix}\begin{bmatrix} N_{11} & N_{12} & N_{13} \\ * & N_{22} & N_{23} \\ * & * & N_{33} \end{bmatrix}\begin{bmatrix} e_1 \\ e_3 \\ e_1 - e_3 \end{bmatrix} + (\eta_M - \eta(t))\mathcal{H}\Big(\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix}\begin{bmatrix} N_{11} & N_{12} & N_{13} \\ * & N_{22} & N_{23} \\ * & * & N_{33} \end{bmatrix}\begin{bmatrix} e_5 \\ 0 \\ e_5 \end{bmatrix}.$$
$$+e_5^T(t)N_2e_5\Big) + \frac{1}{\eta(t)}\begin{bmatrix} e_1^T \\ e_3^T \end{bmatrix}^T\begin{bmatrix} -N_2 & N_2 \\ * & -N_2 \end{bmatrix}\begin{bmatrix} e_1 \\ e_3 \end{bmatrix}$$

Let us now rewrite the disturbed NCS (3.7) *as* $\mathcal{G}\zeta_1(t) = 0$, *with*

$$\mathcal{G} = \begin{bmatrix} A & 0 & BKC & 0 & -I & B_w & BK \end{bmatrix}.$$

Applying Finsler's lemma [45], the closed-loop NCS (3.7) *is asymptotically stable if* $\exists\mathcal{T} \in \mathbb{R}^{7n\times n}$ *such that:*

$$\dot{V}(t) \leq \zeta^T(t)\Big(\Phi_1 + \Phi_2 + \Phi_3(\eta(t)) + \mathcal{H}(\mathcal{T}\mathcal{G})\Big)\zeta(t) < 0 \tag{3.25}$$

Therefore, from the inequality (3.2) *and the* H_∞ *criterion* (3.8), *the inequality* (3.14) *is sufficiently satisfied if:*

$$\begin{aligned} &\dot{V}(t) - e_k^T(t)C^{+T}\mho C^+e_k(t) + y^T(t)y(t) - \gamma^2 w^T(t)w(t) \\ &+ \rho(Cx(t-\eta(t)) + e_k(t))^T C^{+T}\mho C^+(Cx(t-\eta(t)) + e_k(t)) \\ &\leq \Big(\Phi_1 + \Phi_2 + \Phi_3(\eta(t)) + \Xi + \mathcal{H}(\mathcal{T}\mathcal{G})\Big)\zeta(t) < 0 \end{aligned} \tag{3.26}$$

with $\Xi = -e_7^T\mho e_7 + e_1^TC^TCe_1 - \gamma^2 e_6^Te_6 + \rho(Ce_3 + e_7)^TC^{+T}\mho C^+(Ce_3 + e_7)$, *and* $\mho = C^T\Omega C$. *Then Applying Lemma (Lemma 1 in [48]) we obtain the LMIs expressed in Theorem 1. This ends the Proof.*

3.3.2 Control design procedure

Theorem 3.2 *For given constant scalars* $\eta_m > 0, \eta_M > 0$, $\rho > 0$, $\varepsilon_1 \geq 0$ *and* $\varepsilon_2 \geq 0$, *the closed-loop disturbed NCS* (3.7) *is robustly stabilized by the networked controller* (3.6), *under the release instants defined by the ETM condition* (3.2), *with a* H_∞ *disturbance attenuation level* $\gamma > 0$, *if there exist the real matrices* $X > 0$, $\hat{\mathcal{P}} > 0$, $\hat{Q}_1 > 0$, $\hat{Q}_2 > 0$, $\hat{R}_1 > 0$, $\hat{R}_2 > 0$,

$\hat{\mathcal{N}}_1 > 0$, $\hat{N}_2 > 0$, $\hat{\mho} > 0$, $\hat{S}$ and $\hat{K}$ such that the following LMIs are satisfied:

$$\begin{bmatrix} \hat{R}_2 & \hat{S} \\ * & \hat{R}_2 \end{bmatrix} > 0 \tag{3.27}$$

$$\hat{\Phi}_1 + \hat{\Phi}_2 + \hat{\Phi}_3^1 + \hat{\Xi} + \mathcal{H}(\mathcal{X}) < 0 \tag{3.28}$$

$$\hat{\Phi}_1 + \hat{\Phi}_2 + \hat{\Phi}_3^2 + \hat{\Xi} + \mathcal{H}(\mathcal{X}) < 0 \tag{3.29}$$

With:

$$\mathcal{X} = \begin{bmatrix} AX & 0 & \varepsilon_1 B\hat{K} & 0 & -\varepsilon_2 X & B_w & B\hat{K} \end{bmatrix}.$$

$$\hat{\Phi}_1 = \begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} \hat{P}_{11} & \hat{P}_{12} & \hat{P}_{13} \\ * & \hat{P}_{22} & \hat{P}_{23} \\ * & * & \hat{P}_{33} \end{bmatrix} \begin{bmatrix} e_5 \\ 0 \\ e_5 \end{bmatrix}$$

$$\Phi_2 = e_1(\hat{Q}_1 + \hat{Q}_2 - \hat{R}_1)e_1^T - e_2(\hat{R}_1 + \hat{Q}_1)e_2^T - e_4\hat{Q}_2e_4^T + e_1\hat{R}_1e_2^T + e_2\hat{R}_1^Te_1^T + e_5\left(\eta_m^2\hat{R}_1 + (\eta_M - \eta_m)^2\hat{R}_2\right)e_5^T + \begin{bmatrix} e_2^T \\ e_3^T \\ e_4^T \end{bmatrix}^T \begin{bmatrix} -\hat{R}_2 & \hat{R}_2 - \hat{S} & \hat{S} \\ * & -2\hat{R}_2 + \mathcal{H}(\hat{S}) & \hat{R}_2 - \hat{S} \\ * & * & -\hat{R}_2 \end{bmatrix} \begin{bmatrix} e_2 \\ e_3 \\ e_4 \end{bmatrix}$$

$$\Phi_3^1 = -\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} \hat{N}_{11} & \hat{N}_{12} & \hat{N}_{13} \\ * & \hat{N}_{22} & \hat{N}_{23} \\ * & * & \hat{N}_{33} \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \\ e_1 - e_3 \end{bmatrix} + (\eta_M - \eta_m)\mathcal{H}\Bigg(\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} \hat{N}_{11} & \hat{N}_{12} & \hat{N}_{13} \\ * & \hat{N}_{22} & \hat{N}_{23} \\ * & * & \hat{N}_{33} \end{bmatrix} \begin{bmatrix} e_5 \\ 0 \\ e_5 \end{bmatrix} + e_5^T(t)N_2e_5\Bigg) + \frac{1}{\eta_m} \begin{bmatrix} e_1^T \\ e_3^T \end{bmatrix}^T \begin{bmatrix} -\hat{N}_2 & \hat{N}_2 \\ * & -\hat{N}_2 \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \end{bmatrix}$$

$$\Phi_3^2 = -\begin{bmatrix} e_1^T \\ e_3^T \\ e_1^T - e_3^T \end{bmatrix} \begin{bmatrix} \hat{N}_{11} & \hat{N}_{12} & \hat{N}_{13} \\ * & \hat{N}_{22} & \hat{N}_{23} \\ * & * & \hat{N}_{33} \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \\ e_1 - e_3 \end{bmatrix} + \frac{1}{\eta_M} \begin{bmatrix} e_1^T \\ e_3^T \end{bmatrix}^T \begin{bmatrix} -\hat{N}_2 & \hat{N}_2 \\ * & -\hat{N}_2 \end{bmatrix} \begin{bmatrix} e_1 \\ e_3 \end{bmatrix},$$

$$\hat{\Xi} = -e_7^T\hat{\mho}e_7 + e_1^TC_i^TC_ie_1 - \gamma^2e_6^Te_6 + \rho(Ce_3 + e_7)^TC^{+T}\hat{\mho}C^{+}(Ce_3 + e_7)$$

In that case, the gain matrices of the networked controller (3.6) *are obtained by the bijective change of variable* $K = \hat{F}X^{-1}C^{+}$ *and weighting matrix* $\Omega = C^{+T}\mho C^{+}$ *and* $\mho = X^{-T}\tilde{\mho}X^{-1}$ *for the ETM instant released condition* (3.2).

Proof 3.2 *Let $D_X = diag(X^T, X^T, X^T, X^T, X^T, I, X^T)$ with $X \in \mathbb{R}^{n\times n}$. Taking the congruence of* (3.26) *by D_X, with the changes of variables $\hat{\mathcal{P}} = X^T \mathcal{P} X$ $\hat{Q}_1 = X^T Q_1 X$, $\hat{Q}_2 = X^T Q_2 X$, $\hat{R}_1 = X^T R_1 X$, $\hat{R}_2 = X^T R_2 X$, $\hat{\mho} = X^T \mho X$, $\hat{S} = X^T S X$, $\hat{\mathcal{N}}_1 = X^T \mathcal{N}_1 X$ and $\hat{K} = KCX$. Then Applying Lemma (Lemma 1 in [48]) we obtain the LMIs expressed in Theorem 2. This ends the Proof.*

Remark 3.1 *For the proof of Theorem 3.1, we chose a particular case of $\mathcal{T}$, which is filled with* 0 *matrices according to the structure of $\mathcal{G}$ detailed in the Proof. In this special case, two scalars ε_1 and ε_2 are introduced for conservatism reduction, but these have to be pre-specified so that the conditions expressed in Theorem 3.2 are LMIs. Fortunately, these scalars can be tuned offline by linear search, as it is usually done in many Finsler-based approaches (see e.g., [34], [3, 4]).*

3.4 Numerical examples

In order to illustrate the effectiveness of the main results obtained in the previous section, the stability analysis and control design procedure are presented in two subsections. Two cases are presented in such subsection, the first case presents the special case when $i = 1$, the large-scale system converts to the Network control system architecture. In the second case, we present a large-scale system with different values of $i > 1$.

3.4.1 Stability analysis

When the control gains are known we check the stability of the LSS controlled through the network.

3.4.2 Control Design Result

When the control gains are Unknown the control design procedure will be necessitated.

Case 1: Networked Control System: in this case we present two numerical example.

Example 1 : Consider the following NCS model:

$$A = \begin{bmatrix} -2 & 0 \\ 0 & -0.9 \end{bmatrix}, B = \begin{bmatrix} -1 & 0 \\ -1 & -1 \end{bmatrix}, B_w = \begin{bmatrix} 0.1 \\ 0.1 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

By setting the prescribed H_∞ attenuation level to $\gamma = 1$, and with the parameters $\eta_m = 0.1$, $\rho = 0.2$, $\varepsilon_1 = 0.5$ and $\varepsilon_1 = 0.2$, the conditions of Theorem 3.1 have been solved via the Matlab LMI Toolbox this provides a maximal value of $\eta_M = 0.48\,s$, as well as the following sampled-data controller (3.6) gain and ETM matrix:

$$K = \begin{bmatrix} 2.3134 & -0.0000 \\ -2.3134 & 2.3437 \end{bmatrix}, \Omega = \begin{bmatrix} 1.1090 & -0.0000 \\ -0.0000 & 6.6103 \end{bmatrix}.$$

Under the designed sampled-data controller (3.6) and the ETM release condition (3.2), the closed-loop NCS is simulated for this example with the initial condition $x(0) = \begin{bmatrix} -0.5 & 0.5 \end{bmatrix}^T$, an external disturbance signal set as $\omega(t) = 5sin(0.01t)$ when $t \in [0, 5]$, $\omega(t) = 0$ otherwise and $0.1 \leq \eta(t) \leq 0.48$. The state trajectories of the system (3.1) and the release instant and intervals are plotted in Fig.2, and the control signals and the external disturbance are plotted in Fig.3. We can notice that the designed closed-loop NCS is properly stabilized, and achieved the origin in less than $7\,s$, so that, without further changes of the external disturbance, new packet transmissions are not needed.

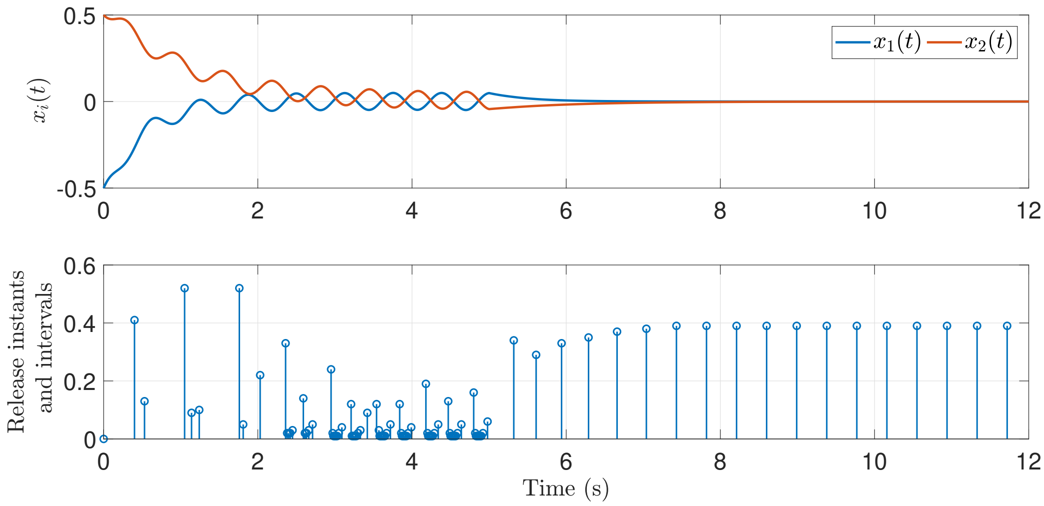

Figure 3.2: States trajectories and release instance and intervals.

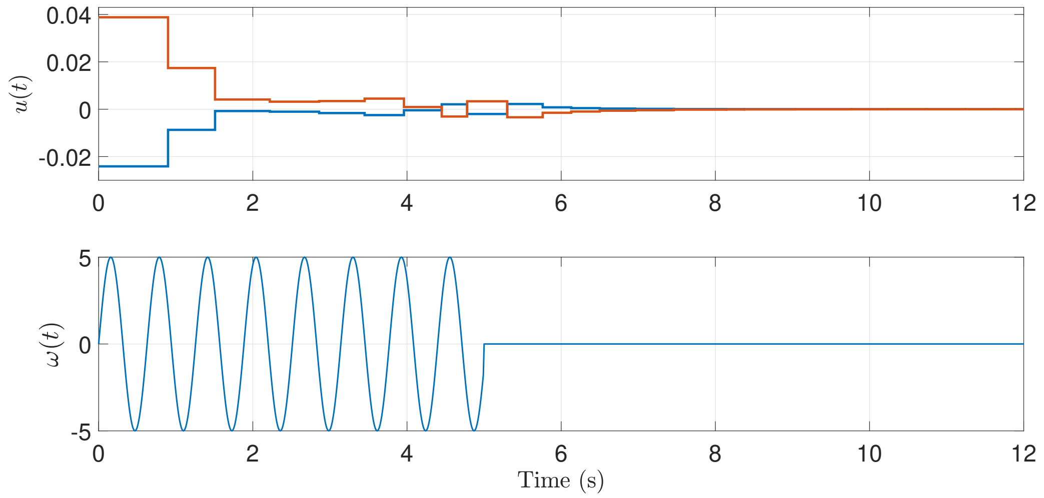

Figure 3.3: Command trajectory and the external disturbance $\omega(t)$.

Example 2: Consider a dynamic model of power systems illustrated in Fig.4, wherein the EVs participate in the LFC scheme in both the second frequency control and primary frequency control of the power system. The state space representation of the power system is described by the following matrices [39, 47].

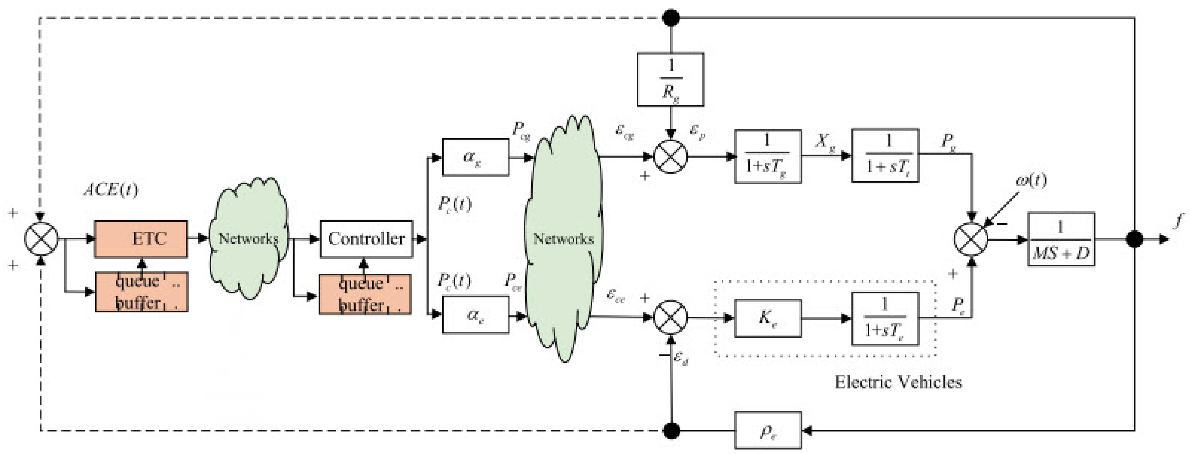

Figure 3.4: Diagram of event-triggered power systems [47].

$$A = \begin{bmatrix} -\frac{D}{M} & 0 & \frac{1}{M} & \frac{1}{M} & 0 \\ -\frac{1}{(Rg*T_g)} & -\frac{1}{T_g} & 0 & 0 & 0 \\ 0 & \frac{1}{T_t} & -\frac{1}{T_t}1 & 0 & 0 \\ -\frac{\rho_e*K_e}{T_e} & 0 & 0 & -\frac{1}{T_e} & 0 \\ b & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ -\frac{\alpha_g}{T_g} \\ 0 \\ \frac{\alpha_e*K_e}{T_e} \\ 0 \end{bmatrix},$$

$$Bw = \begin{bmatrix} \frac{1}{M} & 0 & 0 & 0 & 0 \end{bmatrix}^T, C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

The state and measured output signal are $x^T(t) = \begin{bmatrix} f(t) & X_g(t) & P_g(t) & P_e(t) & \Delta(t) \end{bmatrix}$, $y^T(t) = \begin{bmatrix} f(t) & \Delta(t) \end{bmatrix}$. The parameters of LFC scheme with EVS are given as $D = 0.0083$, $M = 0.1667$, $R_g = 2.4$, $T_g = 0.08$, $T_t = 0.3$, $P_e = \frac{1}{R_g}$, $K_e = 1$, $T_e = 1$, $b = 0.425$, $\alpha_g = 0.8$, $\alpha_e = 0.2$.

Setting the prescribed H_∞ attenuation level to $\gamma = 1$, and the parameters $\eta_m = 0.05$, $\varepsilon_1 = 5\times10^{-3}$, $\varepsilon_2 = 2 \times 10^{-3}$ and $\rho = 0.1$, the conditions of Theorem 3.1 have been solved via the Matlab LMI Toolbox and provide a maximal value of $\eta_M = 0.79\, s$, as well as the following sampled-data controller (3.6) gain matrix and the ETM (3.2) triggering weighting matrix:

$$K = \begin{bmatrix} 0.1574 & 0.1004 \end{bmatrix}, \Omega = 10^5 \times \begin{bmatrix} 0.9990 & 0.9650 \\ 0.9650 & 1.2790 \end{bmatrix}.$$

Assuming $h = 10\,ms$, the allowed maximal network-induced delay is $\tau_M = \eta_M - h = 0.78\, s$. A simulation of the designed closed-loop NCS (3.7) is performed with the initial condition $x_0 = \begin{bmatrix} 1 & 0 & 0.2 & 0 & 0.3 \end{bmatrix}^T$, and an external disturbance signal set as $\omega(t) = sin(0.1t)$ when $t \in [5, 20]$, $\omega(t) = 0$ otherwise. Under the designed release condition (3.2). Fig. 5 depicts the closed-loop state trajectories, release instants, and intervals. The control signals and the external disturbance are plotted in Fig.6. The designed NCS is properly stabilized and achieved the origin in less than 30 s.

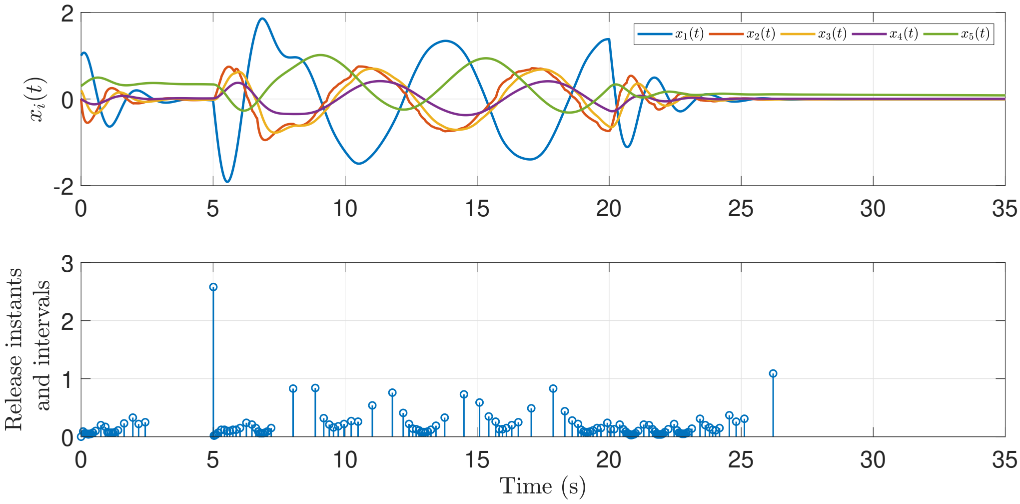

Figure 3.5: States trajectories and release instance and intervals.

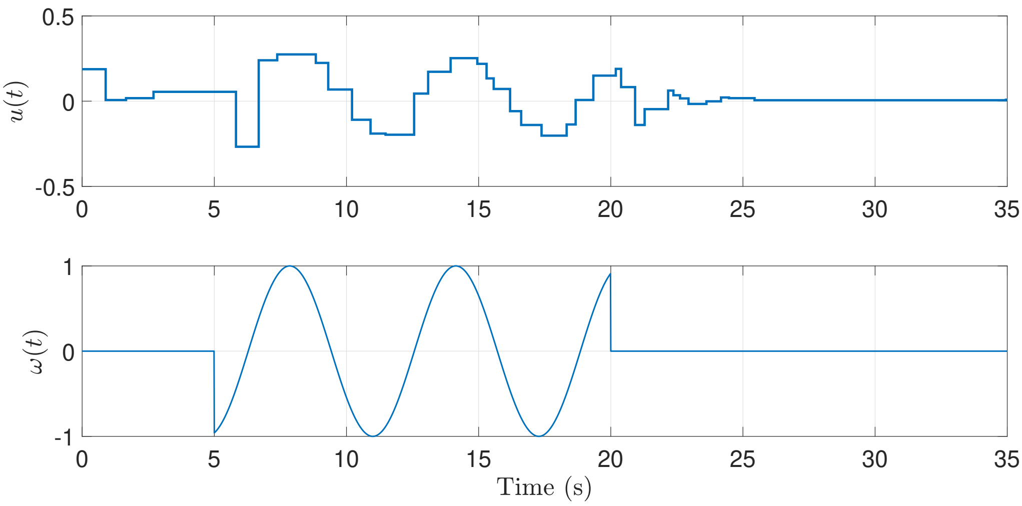

Figure 3.6: Command trajectory and the external disturbance $\omega(t)$.

Moreover, recall that we also aim at avoiding unnecessary transmissions in the designed NCS. Using Theorem 3.1 only 131 (the Transmission Rate (TR =3.27%)) packets are transmitted to the controller node (among 3500 sampled packets) regarding the ETC proposed in [47] that 11.2% of the packets are released by ETC, this confirms the effectiveness of our proposal.

Case 2: Large-scale system: In this case we present a numerical example of chemical reactors consisting of two nonisothermal CSTRs with interconnections between reactors are presented. It is a benchmark for the validation of distributed control algorithms (see [25,69]). The system structure is depicted in Fig.3.7. One can see that the input of CSTR 1 consists of two streams, one containing fresh flow at rate F_0, molar concentration CA_0, and temperature T_0; the second stream contains recycled flow from CSTR 2 at rate F_r, molar concentration CA_2, and tem-

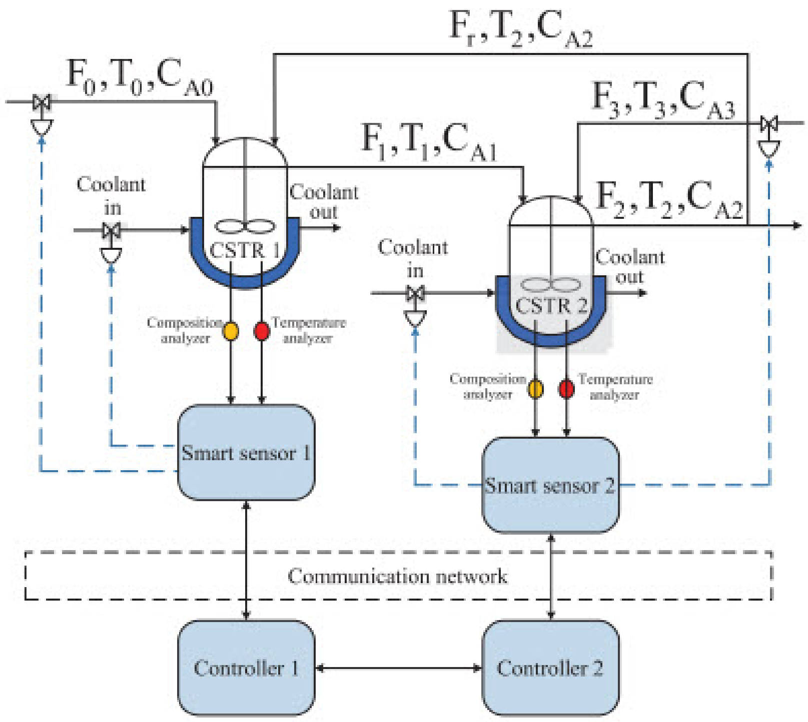

Figure 3.7: Diagram of event-triggered chemical reactor [70].

perature T_2. The input of CSTR 2 consists of an output of CSTR 1, and an additional fresh stream at flow rate F_3, molar concentration CA_{03}, and temperature T_{03}. The smart sensor has the ability to measure the plant and trigger the transmission according to a certain event, and the controller shares their information with each other. The mathematical modeling of CSTR is discussed in [25], the dynamics can be represented by the following equation:

$$\begin{cases} \dot{T}_1 = \frac{F_0}{V_1}(T_0 - T_1) + \frac{F_r}{V_1}(T_2 - T_1) + \sum_{i=1}^{3} G_i(T_1)C_{A1} + \frac{Q_1}{\rho c_p V_1} \\ \dot{C}_{A1} = \frac{F_0}{V_1}(C_{A0} - C_{A1}) + \frac{F_r}{V_1}(C_{A2} - C_{A1}) + \sum_{i=1}^{3} R_i(T_1)C_{A1} \\ \dot{T}_2 = \frac{F_1}{V_2}(T_1 - T_2) + \frac{F_3}{V_2}(T_{03} - T_2) + \sum_{i=1}^{3} G_i(T_2)C_{A2} + \frac{Q_2}{\rho c_p V_2} \\ \dot{C}_{A2} = \frac{F_1}{V_2}(C_{A1} - C_{A2}) + \frac{F_3}{V_2}(C_{A03} - C_{A2}) - \sum_{i=1}^{3} R_i(T_2)C_{A2} \end{cases} \quad (3.30)$$

where $G_i(T_j) = (-(\Delta H_i)/\rho c_p)R_i(T_j)$ and $R_i(T_j) = k_{i0}\exp((-E_i)/RT_i)$ for $j = 1, 2. \Delta H_i, k_{i0}, E_i, i = 1, 2, 3$, denote the enthalpies, pre-exponential constants, and activation energies of the reactions, respectively. c_p and ρ are the heat capacity and density of the fluid in the reactor, respectively. Linearizing the plant equations (3.30) around the operating points $(T_1^s, C_{A1}^s, T_2^s, C_{A2}^s) =$

$457,9\mathrm{K}, 1,77\mathrm{kmol/m^3}, 415,5\mathrm{K}, 1,75\mathrm{kmol/m^3}$ gives

$$\begin{cases} \dot{x}_1(t) = A_{11}x_1(t) + B_1u_1(t) + A_{12}x_2(t) \\ \dot{x}_2(t) = A_{22}x_2(t) + B_2u_2(t) + A_{21}x_1(t) \end{cases}$$

where x_i and u_i are the state and input vector for the i_th subsystem, respectively, and they are defined by

$$x_1 = \begin{bmatrix} \frac{T_1-T_1^s}{T_1^s} \\ \frac{CA_1-C_{A1}^s}{C_{A1}^s} \end{bmatrix}, x_2 = \begin{bmatrix} \frac{T_2-T_2^s}{T_2^s} \\ \frac{CA_2-C_{A2}^s}{C_{A2}^s} \end{bmatrix}$$

$$u_1 = \begin{bmatrix} Q_1 \\ C_{A0} - C_{A0}^s \end{bmatrix}, \quad u_2 = \begin{bmatrix} Q_2 \\ C_{A03} - C_{A03}^s \end{bmatrix},$$

Based on parameters in [25], we have

$$A_1 = \begin{bmatrix} -25.2914 & 4.9707 \\ 78.028 & -45.9368 \end{bmatrix}, B_1 = \begin{bmatrix} 9.45 * 10e-6 & 0 \\ 0 & 2.8234 \end{bmatrix},$$

$$C_1 = \begin{bmatrix} 31.7512 & 0 \\ 0 & 34.6421 \end{bmatrix}, A_2 = \begin{bmatrix} -2.8370 & 1.4157 \\ -22.4506 & -24.8828 \end{bmatrix},$$

$$B_2 = \begin{bmatrix} 3.47 * 10e-6 & 0 \\ 0 & 5.7071 \end{bmatrix}, C_2 = \begin{bmatrix} 14.6953 & 0 \\ 0 & 13.4690 \end{bmatrix}^T,$$

Setting the prescribed H_∞ attenuation level to $\gamma = 1$, and the parameters $\eta_m = 0.05$, $\varepsilon_1 = 5\times10^{-3}$, $\varepsilon_2 = 2\times10^{-3}$ and $\rho = 0.1$, the conditions of Theorem 3.1 have been solved via the Matlab LMI Toolbox and provide a maximal value of $\eta_M = 0.79\,s$, as well as the following sampled-data controller (3.6) gain matrix and the ETM (3.2) triggering weighting matrix:

$$K_1 = \begin{bmatrix} -343.277 & -1695.61 \\ -0.34281 & -0.15070 \end{bmatrix}, \Omega_1 = \begin{bmatrix} 85450.3 & 9315.82 \\ 9315.82 & 1638.77 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} -24237.7 & 10080.4 \\ 0.43380 & -0.21903 \end{bmatrix}, \Omega_2 = \begin{bmatrix} 2740.06 & 975.169 \\ 975.169 & 1029.30 \end{bmatrix}.$$

Assuming $h = 10\,ms$, the allowed maximal network-induced delay is $\tau_M = \eta_M - h = 0.34\,s$. A simulation of the designed closed-loop NCS (3.7) is performed with the initial condition $x_0^1 = \begin{bmatrix} 0.5 & -0.1 \end{bmatrix}^T, x_0^1 = \begin{bmatrix} 0.6 & 0.4 \end{bmatrix}^T$. Under the designed release condition (3.2). Fig. 5

depicts the closed-loop state trajectories, release instants, and intervals. The control signals and the external disturbance are plotted in Fig.6. The designed NCS is properly stabilized and achieved the origin in less than 1 s.

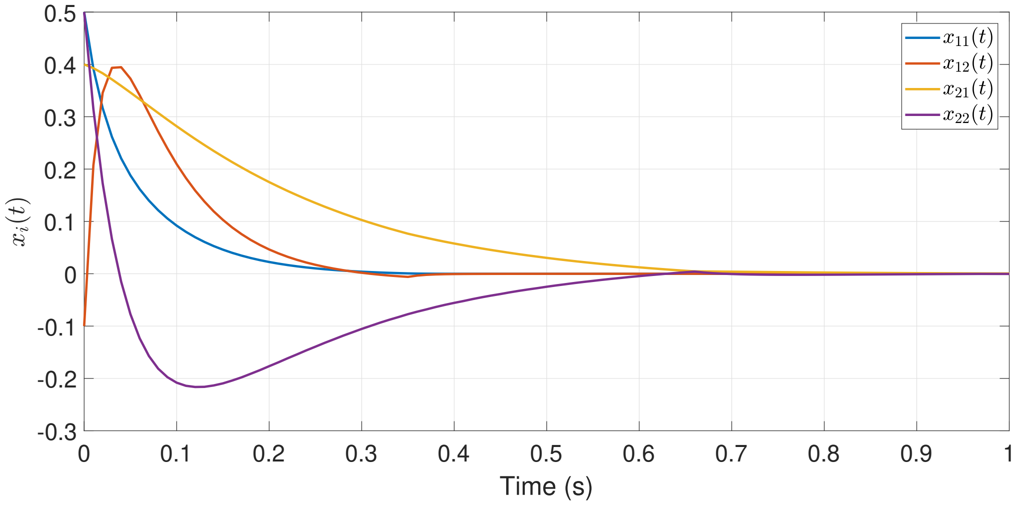

Figure 3.8: States trajectories of large-scale system.

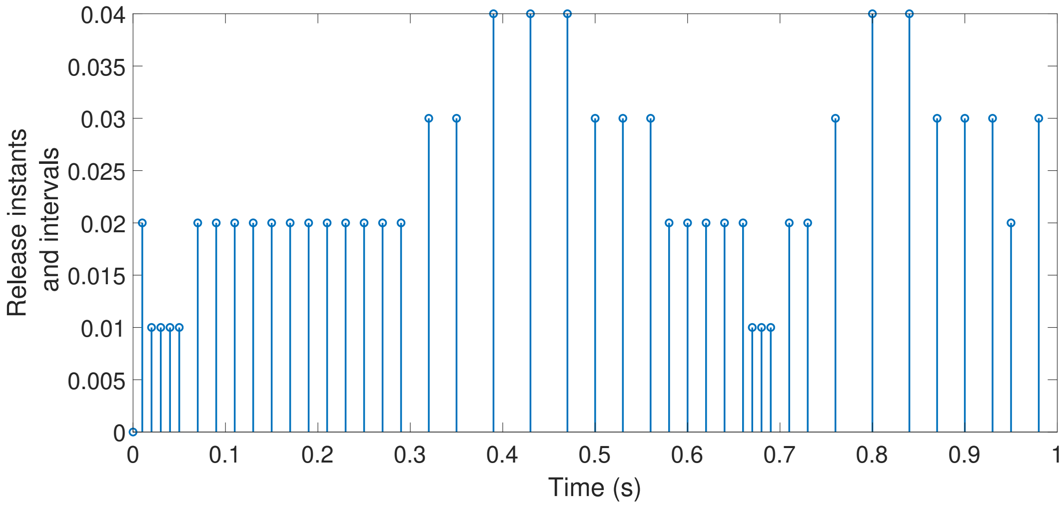

Figure 3.9: Release instants and intervals.

Moreover, recall that we also aim at avoiding unnecessary transmissions in the designed NCS. Using Theorem 3.1 only 43 (the Transmission Rate (TR =43%)) packets are transmitted to the controller node (among 100 sampled packets).

3.5 Conclusion

In this chapter, an event-triggered mechanism (ETM) is proposed to mitigate the network loads in sampled-data controller design for NCSs subject to network-induced delay and external disturbances. The proposed triggering condition is used to reduce the packet transmitted. The goal was to reduce the number of unnecessary transmissions, and so to save network bandwidth, with guaranteed closed-loop stability. Hence, based on the proposed ETM and on the selection of a suitable semi-looped LKF, relaxed LMI-based design conditions have been proposed. Three numerical examples have been considered to illustrate the effectiveness of the proposal.

General Conclusions

This thesis presents several contributions to the design of event-triggered control for Large-Scale Systems (LSSs) subjected to network-induced delay and external disturbances. Since it is not possible to completely avoid these imperfections, they were taken into consideration during the controller design process. Chapter 1 provides an introduction to the field of Large-Scale Systems, including a brief history and recent trends in modeling and solutions for LSSs. Chapter 2 focuses on the principal definitions of LSSs. It also presents different structures for LSSs and discusses their actual implementation in industrial settings and the challenges faced in their modeling and control design. Furthermore, various control techniques used in the study of LSSs are discussed (DCS, SCADA), and the chapter concludes with an overview of the different protocols employed in the real implementation of LSS networks. In Chapter 3, fundamental concepts of stability analysis using the Lyapunov-Krasovskii Functional are presented. Lemmas and theorems related to stability analysis, such as Wirtinger and Jensen's extensions, are discussed to reduce conservatism in stability conditions and estimate the accuracy of resulting time derivatives. Less conservative stability conditions, in the form of linear matrix inequalities (LMIs), are derived by constructing new augmented Lyapunov-Krasovskii functionals (LKFs). The obtained stability condition provides a maximum allowable bound (MAUB) for the network-induced delay that guarantees the stability of Networked Control Systems (NCSs). Next, an event-triggered mechanism (ETM) is proposed to mitigate network load in the sampled-data controller design for NCSs subjected to network-induced delay as we mentioned, and external disturbances. Next, a co-design procedure is developed to determine both trigger parameters and the gains of the proposed networked controller. Finsler's lemma is employed to relax the procedure by introducing slack decision variables and decoupling the system matrices from those of the Lyapunov-Krasovskii functionals. This simplifies the event-triggered control design process to a mere change in variables. Finally, the maximum allowable upper bound of the network-induced delay and event-triggered gains are calculated by solving the convex optimization problem formulated by the relaxed LMIs. Finally, the contributions presented in Chapter 3 are validated through practical numerical examples. The results demonstrate that the negative effects of unpredictable network-induced delays and disturbances with bandwidth limitations are mitigated, ensuring a high level of disturbance attenuation and stability for NCSs

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