

# Chapter 1

## Introduction

### 1.1 Introduction to Networked Control Systems

In recent years, Networked Control Systems (NCS) have gained attraction from researchers due to advancements in communication technologies and the demand for distributed control solutions. Unlike traditional systems, NCSs utilize communication networks to integrate sensors, actuators, and controllers across geographically dispersed locations, offering flexibility and cost-effectiveness in controlling complex systems.

The fundamental concept of NCS involves transmitting sensor data to controllers over the network, which generates control signals for actuators, thereby closing the feedback loop through the network. This approach enhances system maintainability and reduces hardware costs while accommodating diverse sensor and actuator types.

However, integrating communication networks introduces challenges like network-induced delays, congestion risks, and limited bandwidth. Addressing these challenges requires techniques for delay compensation and synchronization, as well as ensuring quality of service to maintain control system stability and performance.

NCSs demand a significant advancement in control theory leveraging communication networks for distributed control and scalability. Overcoming challenges like communication delays and ensuring network reliability is crucial to unlocking their full potential across diverse applications.

## 1.2 NCS architecture

### Background of NCS

The development of NCSs stems from the convergence of control theory and communication technology. Traditionally, control systems operated with localized loops, where sensors, actuators, and controllers were interconnected within closed circuits. The integration of control systems with communication networks emerged as industries adopted computer-based control in the mid-20th century [2, 3]. This evolution enabled remote monitoring and centralized control of distributed processes.

Advancements in communication technologies, such as Ethernet in the 1970s [4], provided a robust framework for connecting control components over shared network mediums. The introduction of Internet Protocol (IP) networks further revolutionized NCS capabilities, facilitating the integration of geographically dispersed systems and enabling decentralized decision-making [5]. Wireless technologies like Wi-Fi and Bluetooth have since expanded the flexibility and mobility of NCS applications across domains such as robotics and healthcare [6].

Research in NCSs focuses on overcoming challenges like communication delays, packet loss, and synchronization issues. Techniques for modeling and compensating network-induced delays ensure system stability, while time synchronization protocols enhance coordination among distributed components [7, 8].

The evolution from traditional control systems to NCSs marks a paradigm shift in control engineering, emphasizing distributed control and real-time data utilization for adaptive strategies [5, 9, 10]. This transition introduces complexities and opportunities, including enhanced system integration, cybersecurity considerations, and the potential for dynamic, efficient control methodologies.

### Traditional control system

A traditional control system operates with a local closed-loop, integrating sensors, actuators, and controllers without communication networks. Sensors measure system parameters, which are compared to a desired reference by the controller. Control signals are generated to adjust actuators and achieve desired system behavior. This approach is straightforward and robust, ensuring reliable control of variables like temperature, pres-

sure, and speed in various applications such as manufacturing and robotics. A traditional control system is shown in Figure 1.1.

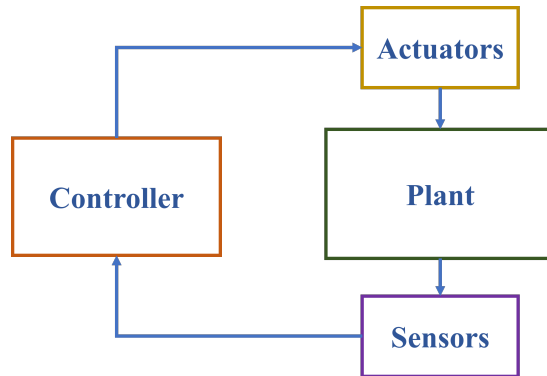


Figure 1.1: The basic structure of a traditional control system

The simplicity of traditional control systems ensures they are resilient to issues like communication delays and network congestion, making them ideal for applications requiring real-time control and high reliability. However, they are less flexible and scalable compared to networked systems. Modifications or additions to control loops necessitate physical alterations to hardware, limiting adaptability in managing complex and distributed control requirements.

### **Networked control system**

NCS integrates control components through a communication network, closing the control loop across geographically distributed sensors, actuators, and controllers. Communication occurs over wired or wireless networks, enabling remote monitoring, coordination, and data exchange among system components. Controllers, whether centralized or distributed, execute control algorithms that manage system behavior and decision-making collaboratively. The structure of an NCS is shown in Figure 1.2.

NCSs introduce complexity beyond traditional systems by integrating communication networks, protocols, and synchronization mechanisms. They necessitate robust solutions for network reliability, addressing challenges such as delays and packet loss. Despite these complexities, NCSs offer scalability and flexibility, facilitating the integration of new components, the addition or removal of control loops, and system reconfiguration without extensive hardware modifications.

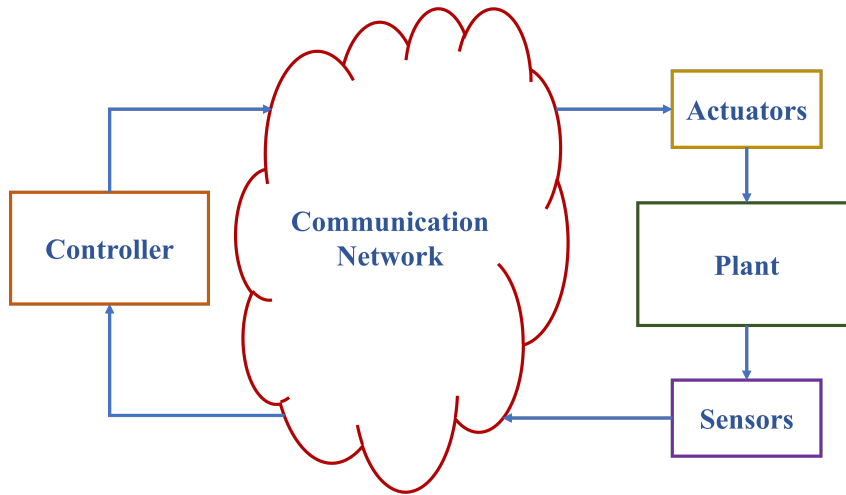


Figure 1.2: The basic structure of a networked control system (NCS)

## NCS applications

The applications of NCSs span various domains, including:

- **Industrial Automation:** NCSs optimize manufacturing processes by coordinating machinery and systems, enhancing efficiency and productivity.
- **Smart Grids:** In energy management, NCSs monitor and control power generation, distribution, and consumption, improving grid reliability and optimizing energy usage.
- **Healthcare:** NCSs enable remote patient monitoring and telemedicine, providing timely medical interventions and improving healthcare delivery.
- **Transportation Systems:** NCSs enhance traffic management, vehicle control, and logistics operations, ensuring safe and efficient transportation networks.
- **Robotics:** NCSs coordinate the actions of multiple robots in complex tasks, enabling collaborative operations and enhancing automation capabilities.
- **Agriculture:** NCSs support precision farming by monitoring soil conditions, irrigation systems, and crop health, optimizing agricultural practices for increased yield and sustainability.
- **Environmental Monitoring:** NCSs facilitate real-time monitoring and control of environmental parameters such as air quality, water quality, and weather conditions,

supporting environmental conservation efforts.

These applications underscore the versatility and utility of NCS in enabling distributed control, remote monitoring, and real-time decision-making across diverse industries and sectors, driving advancements in automation, scalability, and sustainability.

## 1.3 Literature Review

The domain of NCS covers an extensive array of subjects, ranging from fundamental principles to sophisticated control strategies, especially concerning communication challenges. This literature review offers a study of the current research landscape in NCS, comparing state transmission and output transmission, and emphasizing the benefits of output transmission. Additionally, various scheduling algorithms, issues such as delays and dropouts, and predictive control techniques for NCS are examined.

### 1.3.1 State transmission vs Output transmission

In an NCS, information transmission is crucial in ensuring effective communication between the control components distributed across a network. The two primary types of information transmitted in an NCS are state information and output information.

#### State information transmission

The state information (though often estimated instead of directly measured), which includes internal variables describing the system's current condition, is obtained directly using sensors and measurement devices installed on the plant side of NCS. These sensors capture the relevant internal states and provide the measured state information to the controller, as shown in Figure 1.3. In cases where some states are not directly measurable, an observer, often referred to as a state observer or estimator, is employed. The observer uses the available measurable outputs and the system dynamics to estimate the unmeasurable internal states. These estimated states are then transmitted to the controller.

It may be noted that most of the works consider a state feedback controller through an observer as the backbone of the control scheme. In an NCS, the observer can be used either on the plant side [11, 12] or on the controller (remote) side. For the plant-side observer, state information is transmitted through the network.

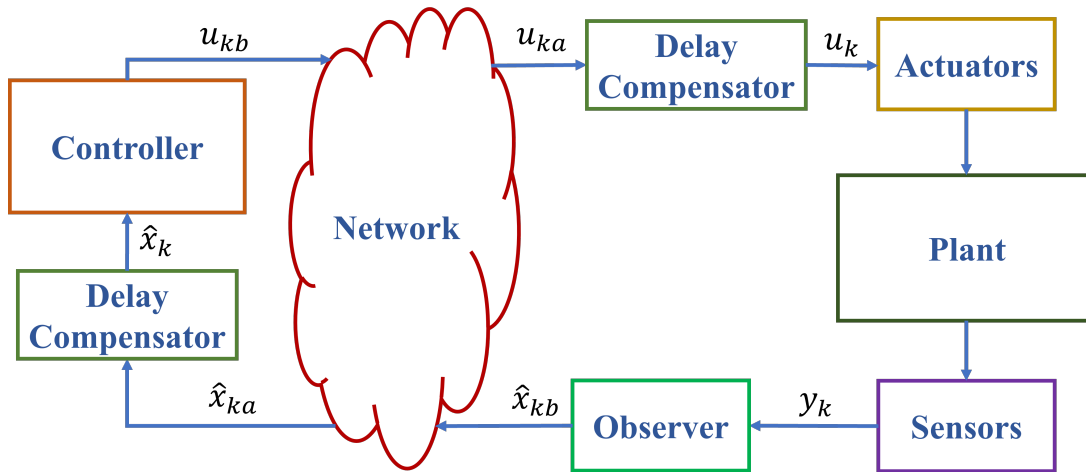


Figure 1.3: State transmission through network

Since packet size is not of concern in literature so far, most of the works considered the transmission of observed state information over the network [13–16], even for applications with a large number of states [17].

### Output information transmission

On the other hand, the measurable output signals representing the system’s responses to control inputs are directly captured by sensors and measurement devices installed on the plant side of NCS. These measured output signals are then transmitted to the controller over the communication network, as shown in Figure 1.4, consisting of an ideal network. The observer then estimates the states using the delayed outputs and the system dynamics. The controller then uses the estimated states to make control decisions.

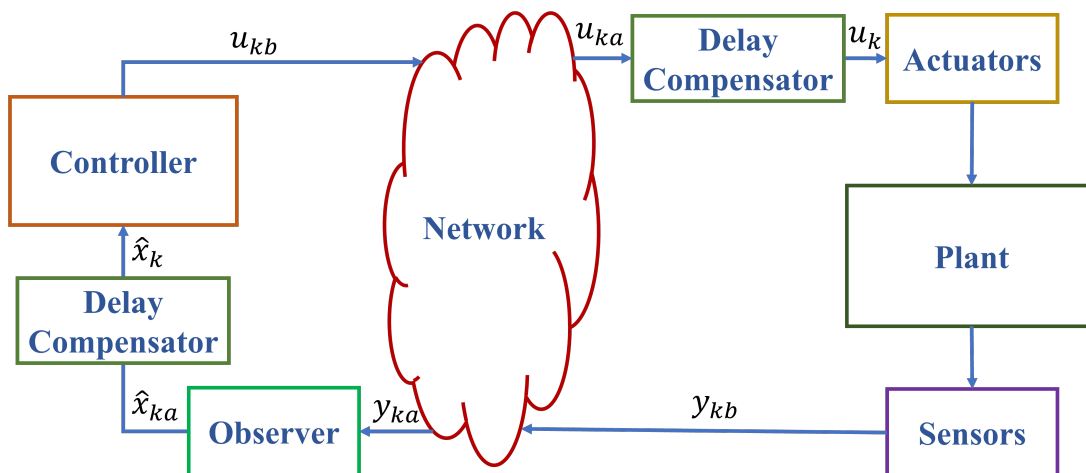


Figure 1.4: Output transmission through network

In this regard, it may be noted that a smaller data packet reduces transmission delay, which is advantageous for an NCS. The size of a data packet is known to affect the network load. The large size of packets causes more transmission delay and reduces communication reliability [18, 19]. Hence, output transmission emphasizes communication efficiency and reduced bandwidth usage leading to an overall impact on control performance.

In an NCS, observer-based control is applied with output transmission and remote observer [20–22]. The existing works lack comprehensive compensation for delays and dropouts using predictive and event-triggered techniques across both channels and do not fully explore the advantages of output transmission over state transmission, which can enhance communication efficiency and reduce packet sizes. This thesis work fills these gaps by introducing sequential output transmission and novel predictive event-triggering techniques that effectively address these challenges, optimizing network utilization and enhancing overall system performance.

It is worthwhile to mention that having an observer on the controller side of an NCS is always advantageous because the transmission of output information requires reduced packet size than the transmission of state information, particularly for systems with a large number of states, given that the size of a packet is limited [18, 23].

### Considerations and trade-offs:

- **Bandwidth constraints:** The available communication bandwidth often influences the choice of transmission between state and output information. State information transmission may be more bandwidth-intensive but offers better information about the states since the observer uses instantaneous input and output information of the plant, while output information transmission may be more bandwidth-efficient.
- **Observability:** The system is better observable when the observer is local to the plant. On the other hand, for output transmission, the construction or estimation of the states from delayed output is complex. This offers the trade-off of the two configurations.
- **Control strategy:** The control strategy employed in the NCS also plays a role. Some control strategies may be designed to operate solely based on output informa-

tion, while others may require detailed state information for optimal performance.

### **Observer considerations:**

- A common choice for state estimation in both cases is the Luenberger observer [24–28], which uses a combination of measured outputs and system dynamics to estimate the internal states.
- In situations with noise and uncertainties, the Kalman filter [29–31] is often employed to estimate the states based on measurements and predictions.
- The choice of observer depends on factors such as the system dynamics, measurement noise, and the desired trade-off between accuracy and computational complexity.

The strategic decision to transmit output rather than the entire state builds upon this foundational understanding. Prioritizing output transmission aligns with efficacy in communication, reduced bandwidth usage and mitigation of network constraints. The inherent benefits of focusing on output information underscore the importance of this strategy in enhancing NCS’s overall efficiency and reliability.

### **Advantages of output transmission**

- **Communication efficacy:** Transmitting output minimizes the amount of data that needs to be transmitted. Focusing on the essential output information makes communication more efficient by reducing data transfer requirements.
- **Reduced bandwidth usage:** Bandwidth is the capacity of the communication channel to transmit data. Transmitting output information typically requires less bandwidth compared to transmitting the entire state. By transmitting only the crucial output data, the network experiences less congestion, improving overall network performance.
- **Mitigation of network constraints:** Network constraints include delays, packet loss, and limited bandwidth. Transmitting output helps address these constraints by minimizing the volume of data transmitted. By carefully selecting critical output

information, the system adapts to and mitigates the effects of network limitations, ensuring more reliable and timely communication.

- **Improved control performance:** Control performance refers to the ability to regulate the system according to desired parameters. Transmitting output enhances control performance by focusing on the essential information for regulation. The control system can make more informed decisions by prioritizing crucial output signals, improving overall performance and stability.

### 1.3.2 Scheduling algorithms

Next, shifting the focus to exploring NCS operating under bandwidth constraints, approaches for efficient bandwidth utilization, adaptive control algorithms, and scheduling mechanisms have been reviewed to ensure optimal performance under limited communication resources. The research covers event-triggered (ET) strategies on both feedback and forward paths, addressing communication efficiency, system stability, and reduced data transmission rates. ET reduces the instants of network communication by determining the usability of new information by comparing the present information with the past.

Scheduling algorithms play a crucial role in NCS to ensure timely and efficient communication between control components over the network. These algorithms determine when and how different control tasks and data packets are scheduled for transmission. The choice of scheduling algorithm in NCS depends on the specific requirements of the control system, including timing constraints, task dependencies, resource availability, and network characteristics. The selected algorithm should ensure timely and efficient execution or transmission of control tasks and data packets, meeting the system's timing requirements while optimizing resource utilization [13, 32–37].

#### **Event-triggering**

In an NCS, while using a communication network, a high rate of periodic communication restricts the performance of the shared network resources [38–41]. Instead of such a periodic communication, Event-Triggered (ET) transmissions are used to build a resource-aware NCS, which intermittently decides and avails the network transmission based on the requirement. The works in [42–45] incorporated such ET in the NCS. A new strategy of

co-designing the observer-based coding-decoding scheme and the N-step MPC is developed in [46] to achieve the expected control performance in a limited-bandwidth network. The constraint imposed by frequent transmission through the network with limited bandwidth is often relaxed using the event-triggering (ET) technique for data transmission [47–50]. ET enables data transmission to be initiated only when a specific event or change in the data occurs, thus reducing the frequency of data transmission and conserving network bandwidth usage [34, 51, 52]. ET is used to overcome the challenges posed by limited bandwidth availability of the network [47, 53].

To address network-induced delays and dropouts and the limited communication resource problem, NCSs use ET integrated along with delay-compensating control through prediction [11, 12, 54, 55]. Only a few studies have utilized ET in both the forward and feedback paths [42, 56, 57]. To overcome the effects of both random delays and dropouts in the network and limited network bandwidth, recent works in [11, 12, 58, 59] emphasized incorporating the Networked Predictive Control (NPC) along with the ETT. In event-triggered control, control signals and feedback information are transmitted based on specific triggering conditions rather than at fixed or periodic intervals.

- **Triggering mechanism:** Event-triggering determines when to initiate control data transmission. It relies on predefined triggering conditions, which can be based on various factors such as the deviation of system variables from desired setpoints, changes in system dynamics, or specific control objectives. These triggering conditions are typically specified by control designers based on the control system’s requirements.
- **Event detection:** The control system continuously monitors the system variables or other relevant signals to detect triggering events. When a triggering event occurs, it indicates that a control action is necessary, and the control system initiates the transmission of control data.
- **Control data transmission:** Upon detecting a triggering event, the control system transmits the relevant control data, such as control signals, sensor measurements, or feedback information, to the appropriate destinations. This transmission can occur through the network infrastructure connecting the control components.

- **Control update:** After transmitting control data, the control components update their control actions based on the received information. The control algorithm recalculates the appropriate control signals or adjusts the control parameters to respond to the triggering event and achieve the desired control objectives.

Below are several approaches for ET:

**Threshold-based triggering:**

This straightforward mechanism compares the current state ( $x_{curr}$ ) to the previously transmitted state ( $x_{prev}$ ) against a predefined threshold ( $\delta$ ). When the difference exceeds the threshold, an event is triggered, indicating the need for information transmission. This approach is useful when significant state changes warrant updates [60].

$$\text{If } \|(x_{curr} - x_{prev})\| \geq \delta, \quad \text{then trigger event.}$$

**Energy-based triggering:**

This mechanism initiates information transmission based on the energy spent by the control input. An event is triggered when the cumulative energy used for control actions surpasses a predefined threshold ( $\epsilon_e$ ) [61].

$$\text{If } \|u\|^2 \geq \epsilon_e, \quad \text{then trigger event.}$$

**Error-based triggering:**

This mechanism initiates information transmission when the control error, the difference between the desired and actual states, exceeds a predefined threshold ( $\epsilon$ ) [62].

$$\text{If } e_u \geq \epsilon, \quad \text{then trigger event.}$$

**Variance-based triggering:**

This mechanism assesses the variability or dispersion of the system state over time and triggers an event when the variance exceeds a predefined threshold ( $\sigma^2$ ) [63, 64].

$$\text{If } \text{Var}(x) \geq \sigma^2, \quad \text{then trigger event.}$$

### Neighbor-based triggering:

This mechanism initiates information transmission based on the difference between the current system state ( $x_{local}$ ) and the state of a neighboring system ( $x_{neighbor}$ ). An event is triggered when this difference exceeds a predefined threshold ( $\delta_n$ ) [65].

$$\text{If } \|(x_{local} - x_{neighbor})\| \geq \delta_n, \quad \text{then trigger event.}$$

### Advantages of using ET in NCS:

Event-triggering in NCSs brings significant benefits such as

- **Reduced communication overhead:** Transmits control data only when necessary, lowering communication costs, reducing network congestion, and improving network utilization.
- **Reduced computation load:** Minimizes unnecessary control calculations and data transmission during stable periods, improving computational efficiency and reducing energy consumption.
- **Increased control system responsiveness:** Triggers control actions immediately upon relevant events, leading to faster system response times and enhanced real-time capabilities.
- **Flexibility and adaptability:** Allows customized triggering conditions based on specific control requirements, enabling tailored mechanisms for system dynamics, performance, or energy constraints.

### Challenges with ET in NCS:

Despite its benefits, event-triggered control also presents challenges, particularly in the areas of

- **Triggering condition design:** Balancing system performance and stability with appropriate triggering conditions is crucial. Poor design can lead to excessive or insufficient triggering, impacting communication, computation costs, and control system performance.

- **Event detection latency:** Detecting triggering events quickly is essential to minimize delays in control actions, ensuring timely response and accurate control.
- **Network-induced delays:** Network communication can introduce delays (packet delays or jitter) affecting the timeliness and reliability of control actions.
- **Synchronization challenges:** Synchronizing event-triggered control across multiple components in a distributed system is complex. Ensuring consistent triggering conditions and maintaining synchronization is vital for proper coordination and control system behavior.

Event-triggering in NCS offers a trade-off between communication/computation costs and control system performance. Event-triggered control can provide efficient and responsive control in networked environments by carefully designing triggering conditions and addressing the associated challenges.

### **Predictive event-triggering**

The concept of predictive event-triggering is reviewed within the context of NCS. Studies investigate how predictive strategies can be leveraged to trigger communication events, anticipate future events, and optimize the timing of data transmissions [32, 66].

#### **Predictive triggering:**

Predictive triggering is an event-triggering mechanism in NCS that initiates information transmission based on the predicted future behavior of the system. Instead of relying solely on the current state, predictive triggering considers the predicted deviation from the desired behavior in the near future. This approach aims to address potential changes in the system state proactively [67–69].

$$\text{If } \|(x_{curr} - \hat{x})\| \geq \delta_p, \quad \text{then trigger event.}$$

Here,  $x$  represents the current state of the system.  $\hat{x}$  is the predicted future state using a model or estimation technique.  $\delta_p$  is the predefined threshold for the difference between the current and predicted states. The triggering condition checks whether the difference  $\|(x_{curr} - \hat{x})\|$  exceeds the predefined threshold  $\delta_p$ . If the condition is satisfied,

an event is triggered, indicating that the system is expected to deviate significantly from the desired behavior soon. Predictive triggering allows for proactive adjustments in anticipation of future changes in the system state. By predicting future states, the triggering mechanism can reduce latency in responding to dynamic system behavior and allot the channel ahead for communication. The effectiveness of predictive triggering relies on the accuracy of the model or estimation technique used to predict future states.

In comparison to ET, predictive triggering (PT) offers to trigger (network communication) through prediction (looking at future state evolution), which makes the triggering more effective, trading off the computational cost involved in the prediction mechanism [66, 70]. It also allows the operator to be notified of available channels in advance, facilitating better network scheduling, particularly for shared networks. There are variants of predictive-triggering, such as Self-Triggering (ST) and Periodic Event-Triggering (PET) [71, 72] that are special cases of generic PT mechanism by restricting or periodically scheduling prediction parameters [73, 74].

### **Time-based triggering or Periodic event-triggering (PET):**

Time-based triggering or Periodic event-triggering (PET) is an event-triggering mechanism in NCS that initiates information transmission at fixed time intervals, regardless of changes in the system state [75]. This approach ensures periodic updates and is particularly useful in scenarios where a consistent refresh rate of information is desired.

Periodic event-triggering (PET) is a triggering scheme that occurs periodically and thus allocates channels at regular and predetermined intervals. PET is employed in various works to allocate channels based on demand [73, 74, 76].

$$\text{If } (t_{curr} - t_{prev}) \geq T_{interval}, \quad \text{then trigger event.}$$

The triggering condition checks whether the time elapsed since the last event trigger ( $t_{curr} - t_{prev}$ ) is greater than or equal to the predefined time interval ( $T_{interval}$ ). An event is triggered if satisfied, indicating it's time to transmit updated information. The main feature of this triggering is the periodic nature of triggering that facilitates predictable communication, aiding in network resource management. Its implementation involves tracking the time since the last event trigger and comparing it to the predefined time interval. A timer or counter in the control system can manage the triggering schedule. It

is suitable for applications where a regular and predictable refresh rate is essential, even if the system state remains relatively constant between updates.

### 1.3.3 NCSs with delays and dropouts

The existing literature on NCS extensively covers the foundational concepts, architectures, and challenges associated with NCS, emphasizing the integration of control and communication systems [7, 8, 77–80]. NCSs face inherent challenges when confronted with communication delays and dropouts [81–84]. This combined set of issues significantly impacts the overall performance and stability of the control system [9, 85, 86]. NCSs involving time-varying transmission intervals and with the competition of multiple nodes accessing networks cause control performance degradation [87–90]. To improve the performance of NCSs subjected to network delays and packet losses, several methods have been proposed [85, 91, 92].

#### Modeling Random delay

In the context of an NCS, producing delayed signals involves intentionally introducing delays. When state information is ready for transmission from the plant to the controller or control information is ready for transmission from the controller to the plant, the transmission time is intentionally shifted. This can be achieved by shifting the time of signal transmission to a random time value generated by a random integer generator with specified minimum and maximum values, as shown in Figure 1.5.

#### Random integer generator:

A random integer generator is a mathematical tool that produces random integers within a specified range. A minimum and maximum value define the range. The random integer generator generates a new random integer each time it is called.

In the context of NCS, the minimum and maximum values specified for the random integer generator determine the range of possible delays. These values define the minimum and maximum delay values in the communication network. For example, if the specified range is between 1 and 10, the random integer generator can produce delays ranging from 1 to 10 time units.

Let  $d_k$  represent the random delay at time  $k$ . The time shift operation can be expressed as  $k - d_k$ , indicating the delay in transmitting the signal.

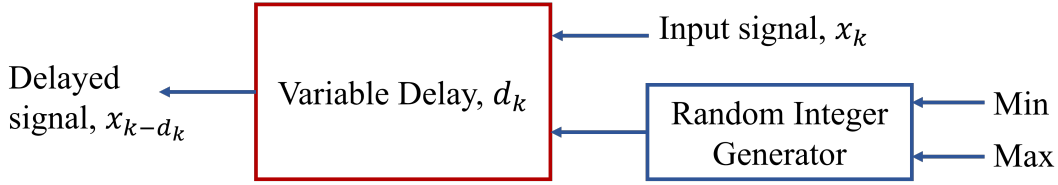


Figure 1.5: Modeling random delays

The intentional time shift introduces delays in the signal communication process. The delays introduced are stochastic, meaning they vary randomly with each transmission. The stochastic nature of delays is essential for capturing the unpredictable characteristics of communication networks, making the NCS model more realistic. The controller and plant must have adaptive control strategies to respond to the varying delays. This ensures that the closed-loop system remains stable and performs well despite the uncertainties in signal transmission times.

Intentionally introducing delays using a random integer generator with specified minimum and maximum values adds a layer of realism to the NCS model. It allows for the simulation of unpredictable communication delays, helping design robust control strategies capable of handling the stochastic nature of networked systems.

### Modeling Random dropouts

In an NCS, simulating communication uncertainties often involves introducing random dropouts, where the communication link experiences intermittent disruptions. The random dropouts can be produced using a random binary number generator to control the switching operation between the input and output, as shown in Figure 1.6.

A random binary number generator randomly produces binary digits (0s and 1s). It produces a new random binary number each time it is activated.

The switching operation determines whether the input signal passes through to the output. When the random binary number equals logic 1, the switch is closed, allowing the input signal to reach the output. This represents a normal transmission without dropout.

The switch opens when the random binary number equals logic 0, the switch opens, indicating a dropout. In this case, the input signal is dropped, and the output does

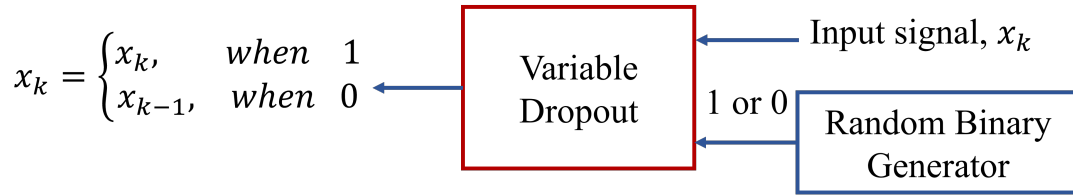


Figure 1.6: Modeling random dropouts

not mirror the input. The random dropouts simulate intermittent disruptions in the communication link. During dropout events (when the random binary number is 0), the output signal does not reflect the input, introducing uncertainties and variability in the communication process. The stochastic nature of dropouts means that the occurrences are random and not predetermined. The randomness mimics the unpredictable characteristics of communication networks, providing a realistic representation of potential disruptions. The control system, both at the controller and plant ends, must incorporate strategies to handle the intermittent dropouts that ensure that the closed-loop system remains stable and adapts to the variations introduced by dropout events.

Introducing random dropouts using a binary number generator adds realism to the simulation of communication uncertainties in NCS. It enables the design and testing of control strategies that can effectively handle intermittent disruptions in the communication link, contributing to the robustness of the NCS in real-world scenarios.

### 1.3.4 Predictive control techniques

In the domain of Networked Control Systems (NCS), managing delays and dropouts is crucial for stability and performance. Non-predictive methods focus on feedback compensation, while predictive methods forecast future states to optimize control actions.

Delay-dependent stability analysis for designing a static output feedback stabilizing controller is discussed in [93]. Stability conditions for NCS with arbitrary and Markovian packet losses using a Lyapunov approach are established in [94]. An output-feedback controller for random packet drops modeled as a Bernoulli process is presented in [95].

Non-predictive methods handle communication delays and dropouts using feedback-based strategies, ensuring system stability and performance with current and delayed state information. Predictive control methods optimize performance within networked communication contexts, leveraging predictive models to adapt to delays, packet losses,

and other uncertainties. Predictive controllers are expected to yield better performance [96]. Delay compensation schemes using Smith predictors are discussed in [97–100].

NCS control can be deterministic or stochastic. The deterministic approach incorporates uncertain variations into the system model [1,11,101], while the stochastic approach uses statistical data for control design [102–104].

Predictive control methods offer advantages by handling time delays, optimizing over a finite prediction horizon, managing constraints, and addressing uncertainties introduced by the communication network. Networked Predictive Control (NPC) generates control predictions using delay and packet loss information. A predictive time-varying output feedback controller is designed in [104] to ensure stability, incorporating a control prediction generator and a network delay compensator. Similar approaches in [20,105,106] ensure system stability. Model-free data-based NPC is discussed in [106]. Predictive control methods counteract delays and uncertainties in NCSs [106–109]. Control methods to address network delays and packet losses in NCS are explored in [110,111]. Predictive schemes for complex NCS, such as cloud-based time-varying formation control for multi-agent systems, are proposed in [112].

Non-predictive methods in NCS include state-feedback control, proportional-integral-derivative (PID) controllers, and other classical control strategies within networked environments.

### **Smith predictor-based control**

In the context of NCS, Smith Predictive Control is a strategy designed to enhance system stability in the presence of communication delays [99]. The Smith Predictor is introduced to estimate future output based on current and past control inputs, and this predictive model is integrated into the overall structure [113]. The control law is designed to minimize the difference between the estimated future output stability [114]. As shown in Figure 1.7, this approach compensates for dead time introduced by delays, providing improved stability and robust performance. However, the Smith predictor works well for constant delay cases and cannot compensate for uncertain delay situations [115].

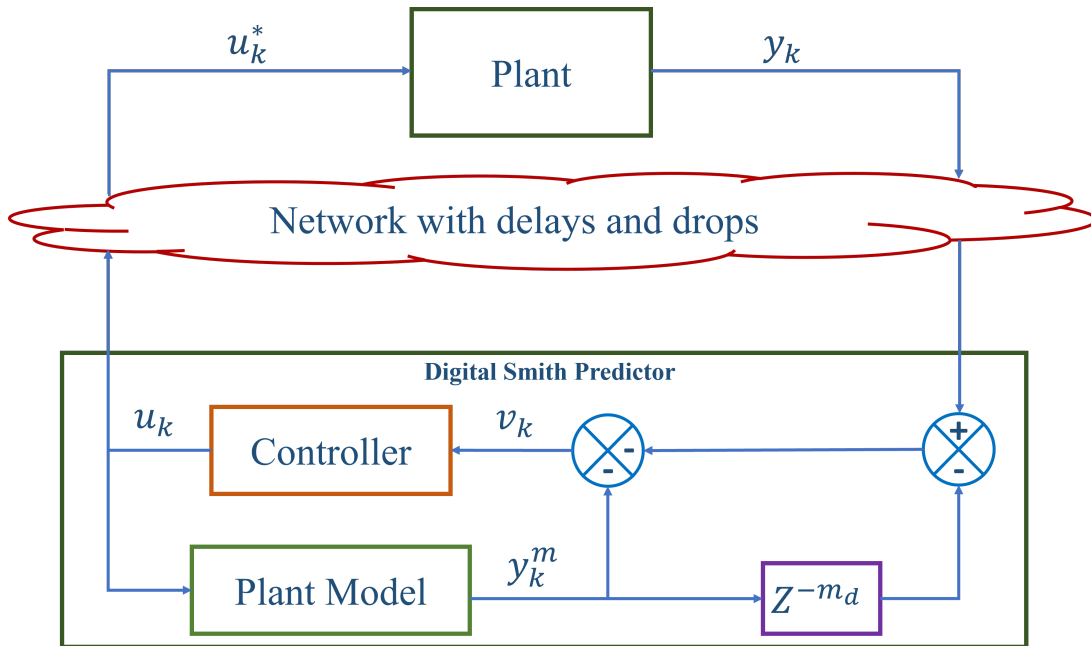


Figure 1.7: NCS with digital Smith predictor

### Model predictive control

Model predictive control (MPC) is a sophisticated control strategy NCSs use to optimize dynamic system performance while adhering to constraints. This method uses a predictive model of the system to optimize control inputs over a finite future time horizon, as shown in Figure 1.8. MPC for NCS is based on a dynamic model of the controlled system. This model predicts system state evolution in response to control inputs. Based on system behavior, MPC optimizes control inputs within the predictive horizon, a finite period. A shorter control horizon is specified in this prediction horizon, and control inputs are adjusted iteratively to optimize system performance [116].

MPC aims to minimize a predefined cost function that includes system states, control inputs, and constraints. The MPC optimization process must consider constraints like control input and system state limits to keep the system safe and feasible. MPC adjusts control inputs based on system state and predicts future behavior as a feedback control strategy. Communication is crucial in NCS because MPC control inputs must be sent to the controlled system. The design accounts for network packet losses and communication delays [117].

Its predictive nature lets it iteratively adjust the control strategy, making it robust to changing network conditions. MPC typically solves the optimization problem at each

time step and applies the first set of control inputs to the system, and thereafter, repeating the process. MPC in NCS has constraint handling, adaptability, and robust performance, requiring computational resources and real-time optimization. Thus, MPC is ideal for systems where these considerations can improve control and optimization [118].

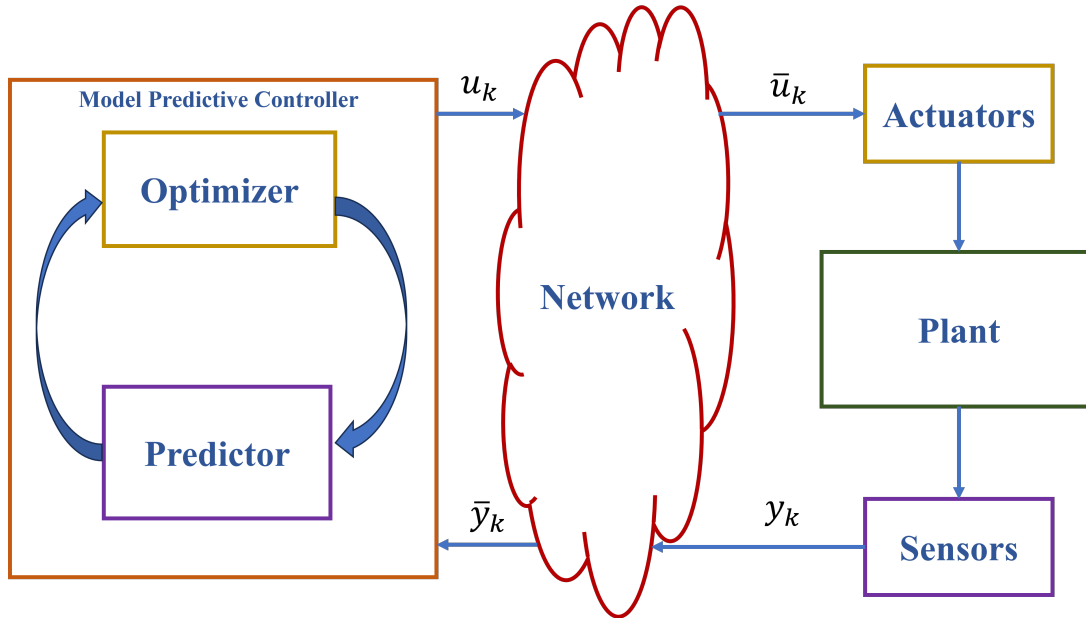


Figure 1.8: NCS with model predictive controller

### Model-based predictive control

Model-based Predictive Control (MBPC), also called Networked Predictive Control (NPC), is a control strategy designed to optimize the performance of dynamic systems within the context of networked communication [11]. This approach combines the principles of predictive control with considerations for the constraints and uncertainties introduced by the communication network, as shown in Figure 1.9. MBPC addresses challenges associated with communication delays, packet losses, and limited bandwidth, making it suitable for applications in networked environments such as industrial automation and distributed control systems [13].

### Key features of MBPC:

- **Dynamic system modeling:** MBPC starts with developing a dynamic model for the controlled system. This model predicts the system's future states based on control inputs.

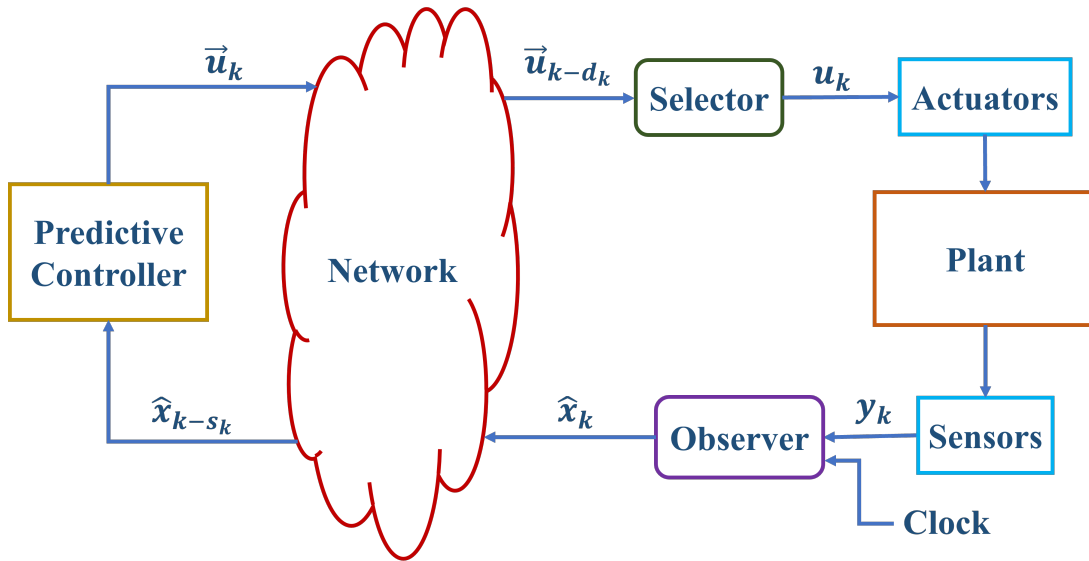


Figure 1.9: NCS with model-based predictive control

- **Communication network modeling:** It incorporates a model for the communication network, considering factors like delays and potential packet losses. This network model is crucial for understanding and adapting to network-induced uncertainties.
- **Prediction horizon:** Similar to model predictive control, NPC operates over a finite prediction horizon. This allows it to make optimal control decisions by considering the anticipated future behavior of the system.
- **Optimization objective:** MBPC aims to minimize a cost function over the prediction horizon. This cost function typically includes terms related to system states, control inputs, and factors specific to network performance.
- **Communication constraints:** MBPC explicitly accounts for communication constraints, optimizing control inputs while respecting the limitations imposed by the communication network. This ensures that the control signals are feasible for transmission.
- **Feedback control:** MBPC is inherently a feedback control strategy, adjusting control inputs based on the current state of the system and predictions for both the system and the communication network.
- **Adaptability to network conditions:** MBPC can adapt to varying network

conditions in real time. The predictive nature of the control strategy allows it to dynamically adjust to changes in communication delays and other network-related parameters.

MBPC finds applications in systems where the interaction between the control system and communication network is critical. By addressing the challenges introduced by network constraints, MBPC ensures the stable and optimized performance of dynamic systems in networked environments.

## 1.4 Challenges in an NCS

NCSs are essential for various modern control applications, enabling remote monitoring and control over communication networks. From the literature review above, it is pertinent that these systems face several significant challenges that impact their performance and reliability as listed in the following:

**Random Network-Induced Delays:** Delays in data transmission can occur unpredictably due to varying network conditions, leading to timing mismatches in control signals and potentially destabilizing the system.

**Packet Dropouts:** Loss of data packets during transmission can disrupt the communication between system components, resulting in incomplete or outdated information being used for control decisions.

**Limited Communication Resources:** The bandwidth and data transmission capabilities of networks are often constrained, necessitating efficient use of available resources to prevent congestion and ensure timely data delivery.

**Network Congestion:** High network traffic can cause delays and packet losses, exacerbating the challenges of maintaining stable and reliable control over the network.

**Conventional Control Methods:** Traditional control strategies often do not account for the complexities introduced by network conditions, such as delays and dropouts, leading to suboptimal system performance and reduced reliability.

**Event-Triggered Methods Limitations:** While Event-Triggered (ET) control methods help reduce unnecessary communication, they primarily focus on the feedback path and may not fully exploit the potential benefits of implementing ET on both feedback and forward paths.

**State Transmission Practices:** The conventional practice of transmitting state information can result in large packet sizes, increasing the likelihood of delays and packet loss, and contributing to network congestion.

## 1.5 Motivation for the research

Given the significant challenges faced by NCSs, there is a pressing need for innovative strategies to enhance their performance and reliability. The motivation for this research is driven by several key factors:

**Efficiency and Reliability:** Improving the efficiency of data transmission and the robustness of control strategies may enhance the overall performance of NCSs.

**Event-Triggered Control:** This approach has shown promise in reducing unnecessary communication and optimizing network utilization, but it requires further exploration and refinement.

**Output Transmission Techniques:** Shifting from state transmission to output transmission can reduce packet sizes and alleviate network congestion, leading to better performance. The aspects of output transmission have not been emphasized in the literature.

**Predictive Control Strategies:** Implementing predictive control strategies is crucial for mitigating the adverse effects of delays and packet drops. These strategies anticipate potential disruptions and adjust control actions accordingly, ensuring stable and efficient system performance even under adverse network conditions. Predictive control with output transmission is an open problem in existing literature.

**Predictive Triggering:** Developing advanced predictive triggering techniques can help overcome the limitations of traditional methods, ensuring more reliable control in the face of network-induced delays and dropouts.

## 1.6 Aim and Objectives of the thesis

### **Aim:**

The aim of this thesis is to develop and implement advanced strategies for enhancing the performance, efficacy, and robustness of Networked Control Systems (NCSs) by addressing

challenges associated with random delays, packet dropouts, and limited communication resources.

### **Objectives:**

The key objectives that are addressed in this work are as follows:

- To investigate the trade-offs in transmitting output information instead of state information. Transmitting output information highlights benefits such as smaller packet communication, thereby improving network usage, and possibly lesser delay and packet losses.
- To study Event-Triggered (ET) methods on both the feedback and forward paths of NCSs to address bandwidth constraints.
- To develop a predictive control technique for output transmission.
- To investigate methods for improving state observer performance from delayed output information.
- To develop predictive triggering techniques to overcome limitations associated with traditional event-triggering methods for NCS with output transmission.

## **1.7 Contributions and Thesis outline**

This thesis is organized into several chapters, each thoroughly addressing specific aspects of the research problem and objectives. The following provides a comprehensive overview of the contribution and content of the thesis:

### **Chapter 1 - Introduction:**

As seen, this chapter introduces NCS, focusing on their architecture and the challenges of network delays and packet drops, which motivate this research. It reviews the evolution of NCS and communication technologies, highlighting the advantages of output transmission over state transmission, as well as event-triggered and predictive control techniques. The chapter sets the thesis objectives to enhance NCS performance through innovative methodologies and outlines the contributions

## **Chapter 2 - Predictive control of networked control system with event-triggering in two channels:**

This chapter delves into implementing event-triggered communication in NCSs, focusing on feedback and forward channels. It emphasizes the advantages of reduced data transfer rates through predictive control, even in the face of significant random delays and packet drops, ensuring robust closed-loop control performance. A key contribution here is the development of comprehensive strategies for compensating delays and dropouts, and the introduction of innovative techniques for output transmission instead of state transmission. The approach prioritizes output transmission over state information, introducing the concept of a remote observer and strategically exploring event-triggering methods on both communication paths. This work led to the following publication:

- Haritha Mittapally, Sandip Ghosh, and Shyam Kamal, “Predictive control of networked control system with event-triggering in two channels,” *European Journal of Control*, vol. 72, 2023.

## **Chapter 3 - Sequential output information-based predictive control for event-triggered networked control systems:**

Presenting a novel scheme, this chapter incorporates sequential output information transmission to enhance state observer performance. This sequential approach, combined with event-triggering, significantly improves transmission efficiency by optimizing network constraints such as delays, dropouts, and packet size. The research introduces the concept of sequential output transmission techniques, a significant contribution aimed at enhancing NCS performance and overall efficiency, effectively addressing network limitations. This work is published as the following paper:

- Haritha Mittapally, Sandip Ghosh, Shyam Kamal, and Pawel Dworak, “Sequential output information based predictive control for event-triggered networked control systems,” *ISA Transactions*, 2024.

## **Chapter 4 - Predictive-triggered compensating control for networked control systems with random delays and dropouts:**

This chapter introduces innovative predictive triggering techniques that surpass the limitations of traditional event-triggered approaches. The techniques are designed to optimize network utilization by reducing network usage and preemptively updating the network operator. A major contribution is the emphasis on the advantages of transmitting output information over state transmission, which results in smaller packet communication and reduced computational efforts at various communication nodes. These advancements enhance the robustness of NCS in the presence of large delays and dropouts due to both network conditions and event-triggering. This work is communicated to a journal for possible publication as the following:

- Haritha Mittapally, Sandip Ghosh, Shyam Kamal, and Pawel Dworak, “Predictive-triggered compensating control for networked control systems with random delays and dropouts,” (Under review)

## **Chapter 5 - Conclusions and future scopes:**

The final chapter encapsulates the conclusions drawn from the research findings and outlines paths for future exploration and expansion of the study. It serves as a reflection on the achieved outcomes and a guide for potential research directions.