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Age of Information Aware Communication Systems

Modeling and Performance Analysis

Antzela Kosta

LINKÖPING UNIVERSITY

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To my friends and family

We may know the past but cannot control it. We may control the future but cannot know it.
–Claude E. Shannon

Abstract

Advances in wireless communications and networking technology have taken us towards a pervasively connected world in which a vast array of wireless devices, from mobile phones to environmental sensors, seamlessly communicate with each other. In many of these systems the freshness of the transmitted information is of high importance. Characterization of time-critical information can be achieved through the so-called real-time status updates that are messages, encapsulated in packets, carrying the timestamp of their generation. Status updates track time-varying content that needs to be transmitted from the generation point to a remote destination in a network. To quantify the freshness of information in networked systems, a novel metric, different from delay or latency, termed as "age of information" (AoI) has been introduced. In this thesis, we focus on characterizing and controlling age under various communication system setups.

The first part of the thesis considers multiple access communication systems and comprises two papers. The first paper, investigates AoI in relation with throughput in a shared access setup with heterogeneous traffic. More specifically, we consider a shared access system consisting of a primary link and a network of secondary nodes, with multipacket reception (MPR) capabilities. To study the joint throughput-timeliness performance, we formulate two optimization problems considering both objectives and provide guidelines for the design of such a multiple access system satisfying both timeliness and throughput requirements.

In the second paper, we study the AoI performance in various multiple access schemes, including scheduling and random access. We present an analysis of the AoI with and without packet management at the transmission queue of the source nodes, considering that packet management is the capability to replace unserved packets in the queue whenever newer ones arrive. We incorporate the effect of

channel fading and network path diversity in such a system and provide simulation results that illustrate the impact of network operating parameters on the performance of the considered access protocols.

The second part of the thesis considers the characterization of AoI and other freshness performance metrics in a point-to-point communication link, again comprising two papers. In the third paper of this thesis, we expand the concept of information ageing by introducing the cost of update delay (CoUD) metric to characterize the cost of having stale information at the destination. Furthermore, we introduce the value of information of update (VoIU) metric that captures the degree of importance of the update received at the destination. We employ queue-theoretic concepts and provide a theoretical analysis and insights into the prospects of cost and value.

Finally, in the last paper, we study the properties of a sample path of the AoI process, and we obtain a general formula of its stationary distribution. We relate this result to a discrete time queueing system and provide a general expression of the generating function of AoI in relation with the system time, and the peak age of information (PAoI). To illustrate the applicability of the results, we analyze the AoI in single-server queues with different disciplines and assumptions. We build upon these results to provide a methodology for analyzing general non-linear age functions for this type of systems.

Populärvetenskaplig sammanfattning

Framstegen inom trådlös kommunikation och nätverksteknologi har tagit oss mot en genomgripande ansluten värld där ett stort antal trådlösa enheter, från mobiltelefoner till miljösensorer, sömlöst kommunicerar med varandra. I många av dessa system är färskheten hos den överförda informationen av stor betydelse. Karaktärisering av tidskritisk information kan uppnås genom de så kallade realtidsstatusuppdateringarna som är meddelanden, inkapslade i paket, som har en tidsstämpel för när det genererades. Statusuppdateringar spårar tidsvarierande innehåll som måste överföras från genereringspunkten till en avlägsen destination i ett nätverk. För att kvantifiera informationens färskhet i nätverkssystem har ett nytt mått, som skiljer sig från fördröjning, benämnd "informationsålder" (AoI) införts. I denna avhandling fokuserar vi på att karakterisera och kontrollera denna ålder för olika uppsättningar av kommunikationssystem.

Den första delen av avhandlingen behandlar flera accesskommunikationssystem och innehåller två artiklar. Den första artikeln undersöker AoI i relation till genomströmning i en uppsättning med delad åtkomst med heterogen trafik. Mer specifikt överväger vi ett system för delad åtkomst som består av en primär länk och ett nätverk av sekundära noder, med multipaketmottagning (MPR). För att studera prestanda för gemensam genomströmning-aktualitet formulerar vi två optimeringsproblem med beaktande av båda målen och tillhandahåller riktlinjer för utformningen av ett sådant fleranvändarsystem som uppfyller både krav på tid och kapacitet.

I den andra artikeln studerar vi AoI-prestanda för olika scheman av fleranvändaraccess, inklusive schemaläggning och slumpmässig åtkomst. Vi presenterar en analys av AoI med och utan pakethantering i överföringskön för källnoderna, där pakethantering är förmågan att ersätta ej hanterade paket i kön när nyare kommer. Vi integrerar effekten av kanalfädning och länkdiversitet i ett sådant system och ger simuleringsresultat som illustrerar inverkan av nätverksoperatörsparametrar på prestanda för de valda åtkomstprotokollen.

Den andra delen av avhandlingen behandlar karaktäriseringen av AoI och andra relevanta prestandamått i en punkt-till-punkt-kommunikationslänk och även denna består av två artiklar. I den tredje artikeln i denna avhandling utvidgar vi konceptet för åldrande av information genom att införa kostnaden för uppdateringsfördröjning (CoUD) för att karakterisera kostnaden för att ha inaktuell information på destinationen. Dessutom introducerar vi värdet på information om uppdatering (VoIU)-måttet som fångar graden av betydelse för uppdateringen som mottagits vid destinationen. Vi använder köteoretiska begrepp och ger en teoretisk analys och insikter om utsikterna för kostnad och värde.

Slutligen, i den sista artikeln, studerar vi egenskaperna för en exempelrutt för AoI-processen, och vi får en allmän formel för dess stationära distribution. Vi relaterar detta resultat till ett diskret tidskösystem och ger ett generellt uttryck för AoIs genererande funktion i förhållande till systemtiden och informationens högsta ålder (PAoI). För att illustrera användbarheten av resultaten analyserar vi AoI i kön med en server med olika discipliner och antaganden. Vi bygger vidare på dessa resultat för att tillhandahålla en metod för analys av allmänna icke-linjära åldersfunktioner för denna typ av system.

Acknowledgments

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A special thanks goes to my dear friend Ioanna Chalkiadaki who designed the cover of this dissertation and to all my friends in Greece who have always been supportive and a source of joy throughout the years.

Above all, I would like to thank my parents and my brother, for the unconditional love, motivation, and support they always provide me. If it wasn't for them I wouldn't be where I am today. I dedicate this thesis to them and to my grandpa Michalis as a small return for all these signed books he has given me over the years.

Norrköping, May 2020
Antzela Kosta

Abbreviations

AoI	age of information
AoII	age of incorrect information
AoS	age of synchronization
AP	access point
BS	base station
CoUD	cost of update delay
CSI	channel state information
EAoI	effective age of information
FCFS	first-come-first-served
FDD	frequency division duplex
FSMC	finite state Markov channel
HARQ	hybrid automatic repeat request
ICT	information and communication technologies
ILP	integer linear programming
IoT	internet of things
LST	Laplace-Stieltjes transform
LCFS	last-come-first-served
LTE	Long Term Evolution

MASP minimum age scheduling problem

MDP Markov decision processes

MGF moment generating function

MPR multipacket reception

OU Ornstein-Uhlenbeck

PAoI peak age of information

PCoUD peak cost of update delay

QoS quality of service

rAoI relative age of information

SHS stochastic hybrid systems

UAV unmanned aerial vehicle

UEs user equipments

VoIU value of information of update

WSN wireless sensor networks

Contents

Part I

Introduction and Overview

Chapter 1

Introduction

1.1 Motivation

The explosive growth of information and communication technologies (ICT) has led to an increasingly connected world in which information is generated and exchanged among different entities. Wireless communications over the last decades have spurred technological advances that allow seamless connectivity, enhanced quality of service (QoS), and high reliability, even under high mobility. Fostered by the rapid proliferation of wireless communication devices, the internet of things (IoT) is present with applications bearing challenging requirements on the network and communication infrastructure [1].

For decades, among the most critical performance indicators, for current and future networks have been end-to-end delay, throughput, energy efficiency, and service reliability. The concept of *age of information* (AoI) was introduced in 2011 to quantify the freshness of the knowledge we have about the status of a remote system [2, 3]. The *age* captures the time elapsed since the last received message containing update information, was generated. This metric has attracted a vivid interest over the last years, due to its novelty to characterize the freshness of information in a communication system, that differentiates it from other conventional metrics such as delay.

Time-critical information in a monitoring system can be characterized through *real-time status updates* in the form of packets. Such packets contain (i) the status update information and (ii) a timestamp of their generation. Status updates can range from sensor observations to stock market data, and track time-varying content that needs to be transmitted from the generation point to a remote destination within a network.

The timeliness of status updates was first investigated in the context of vehicular networks [2, 3], where the authors addressed the broadcast problem. In particular, sensor nodes capturing velocity, acceleration, parking radars measurements etc., disseminate this time-critical content to interconnected vehicles across the network to improve road safety and transportation efficiency [4]. Maintaining data freshness is a requirement in numerous other applications like wireless sensor networks (WSN) for healthcare and environmental monitoring [5, 6], active data warehousing [7], content caching [8, 9, 10, 11], real-time databases [12], ad hoc networks [13, 14], wireless smart camera networks [15, 16], unmanned aerial vehicle (UAV)-assisted IoT networks [17, 18], broadcast wireless networks [19, 20, 21], and the efficient design of freshness-aware IoT [22].

Furthermore, in the field of adaptive transmission significant efficiency gains can be obtained by adaptive signaling strategies (e.g. modulation and coding) [23, 24]. However, this feedback scheme is constrained by the acquisition of channel state information (CSI). Obtaining instantaneous CSI incurs significant communication overhead, and delayed CSI could affect the performance of algorithms especially when channels vary rapidly in a dynamic environment. The notion of timeliness as captured by age can be studied in considerably diverse systems in the form of either a concept, a performance metric, or a tool, as we have discussed at length in [25].

Approaching information transmission in the context of timeliness gives rise to a number of problems where AoI can be considered as a concept to be incorporated in already existing communication systems. Already in the first seminal work of [26] that rigorously analyzes the AoI, it became clear that keeping a destination timely updated about a remote system is neither the same as maximizing the utilization of the communication system, nor of ensuring that the packets are received with minimum delay. In the queueing model studied therein, the resources were limited and the source can generate status updates with a certain average arrival rate. Given a service rate, utilization is then maximized by generating status updates that are to be delivered to the destination as fast as possible. However, this could lead to outdated information at the destination since packets would be backlogged in the system. On the other hand, significantly decreasing the system utilization by reducing the average arrival rate leads to stale information at the destination due to the absence of updates. Minimizing AoI gives a non-trivial timeliness-optimal solution that maximizes the freshness of information at the destination.

In addition to the introduction of age as a concept, AoI can be modeled and used as a performance metric together with various relevant metrics derived in relation to it, such as the peak age of information (PAoI) [27], the cost of update delay (CoUD) [28, 29], also referred to as non-linear age penalty function [30], the value of information of update (VoIU) [28, 29, 31], the age of synchronization (AoS) [32], and the age of incorrect information (AoII) [33], to name a few. Towards this direction, general methods for calculating the AoI of a system as well as deriving upper and lower bounds, have been addressed in the literature. A primary question that arises is how to determine the optimal policy that minimizes the average or instantaneous age in a status update system. To this end, optimization problems and algorithms have been formulated that contribute to the design of information-update systems.

As mentioned earlier, maintaining the timeliness of data while effectively utilizing the available resources is a critical objective in many communication systems. However, depending on the application context, there is a wide range of objectives to be considered by system designers. There have been a number of works presenting how the concept of AoI and its relevant metrics can be incorporated in various areas, such as game theory [34, 35] or reinforcement learning [36, 37, 38]. The number of domains in which AoI can be treated as a tool to facilitate the timely update of information in a system, is quite diverse. Some domains considered until now in the literature are scheduling, energy harvesting, CSI estimation, learning, source and channel coding, monitoring and control, IoT, and caching. More detailed discussions of these topics can be found in Chapter 3.

1.2 Thesis Outline and Organization

The thesis is divided into two parts. In Part I, we provide a general introduction into the concept of AoI, the relevant timeliness performance metrics, and the communication setup, related to our work. Part II contains the research papers that complete this dissertation. Part I is organized as follows. In Chapter 2, we introduce the AoI metric along with the by-product metrics of the AoI, and present a general framework of analyzing time averages as well as the AoI stationary distribution. In Chapter 3, we consider the problem of AoI minimization under various system setups and solution tools. In Chapter 4, we provide a short description of the contributions for each paper appended in Part II.

Chapter 2

Information Freshness

In this chapter, we establish the fundamentals of the timeliness of information in status update systems. We begin with the definition of the AoI metric and proceed with the general framework of analyzing the time average AoI as well as the AoI stationary distribution. Both the average age and its distribution can be utilized to characterize the information freshness performance of a system. Finally, we present a variety of performance metrics spawned by AoI that provide alternative research directions.

2.1 The Age of Information Metric

Consider a communication system consisting of two nodes. A stochastic process $X(t)$ is observed by the source node, that extracts samples from it, as shown in Figure 2.1. These carry information about the status of the process at the source node. Assuming this status information is needed at the destination node, each collected sample needs to be transmitted over a communication link to reach the destination. The source node is equipped with a buffer that stores the samples in the form of packets containing (i) the value of the process $X(t_i)$, at time t_i when the ith sample was extracted and (ii) the timestamp t_i. Packets are sent along the communication link of the two nodes. Each such *packet* arriving at the destination, provides a *status update* and these two terms are used interchangeably.

A simple queueing model is employed, as shown in Figure 2.2, where all packets $i = 1, 2, \ldots$ generated at the source s need to reach

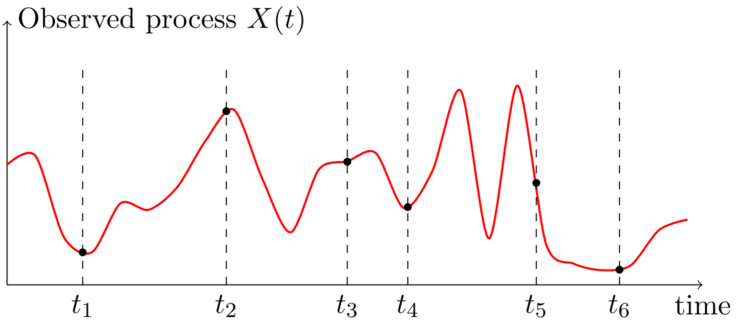

Figure 2.1: Sampling the stochastic process of interest.

the destination denoted by d. The storage of the packets at the queue is instantaneous, thus the packet arrivals at the queue are characterized by the sampling rate of $X(t)$ and so the terms *status update generation* and *packet arrival* can be used interchangeably. Consider that the status update generation is modeled as a stochastic process of average rate λ and packets are then transmitted with an average service rate μ.

The freshness of the knowledge the destination has for the status of the source node is captured by the concept of the AoI. With AoI this freshness is quantified, at any moment, as the time elapsed since the last received status update was generated by the source.

Definition 1 (Age of Information – AoI)**.** *Consider a system comprising a source-destination communication pair. Let $t_k^{'}$ be the times at which status updates are received at the destination. At time ξ, the index of the most recently received update is*

$$N(\xi) = \max\{k|t_k^{'} \leq \xi\}, \tag{2.1}$$

and the timestamp of the most recently received update is

$$u(\xi) = t_{N(\xi)}. \tag{2.2}$$

The age of information (AoI) of the source s at the destination d is then defined as the random process

$$\Delta(t) = t - u(t). \tag{2.3}$$

Figure 2.3 shows an illustrative example of the evolution of AoI in time. Without loss of generality, assume that at $t = 0$ we start observing the system, the queue is empty, and the AoI at the destination

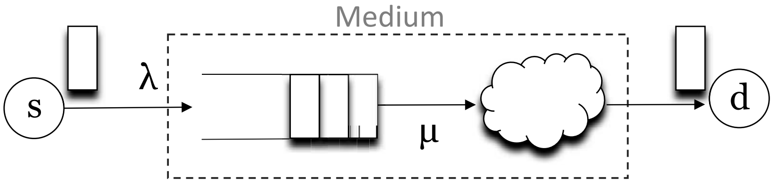

Figure 2.2: The basic system model.

is $\Delta(0) = \Delta_0$. Status update i is generated at time t_i and is received by the destination at time $t_i^{'}$. Between $t_{i-1}^{'}$ and $t_i^{'}$, when there is an absence of updates at the destination, the AoI increases linearly with time. Upon reception of a status update the AoI is reset to the delay that the packet experienced going through the transmission medium. This delay equals the system time defined below.

The ith interarrival time is defined as the time elapsed between the generation of update i and the previous update generation, thus Y_i is the random variable

$$Y_i = t_i - t_{i-1}. \tag{2.4}$$

Moreover,

$$T_i = t_i' - t_i, \tag{2.5}$$

is the system time of update i, corresponding to the sum of the queue waiting time and the service time. Assuming that the observation interval is from $t = 0$ to $t = \mathcal{T} = t_n'$, we denote by

$$N(\mathcal{T}) = \max\{n|t_n \leq \mathcal{T}\}, \tag{2.6}$$

the number of arrivals by time $\mathcal{T}$. Then, at times t_i' for $i = \{1, 2, \ldots, N(\mathcal{T})\}$ the age $\Delta(t_i')$ is reset to $T_i = t_i' - t_i$. The reduction in age with each received update captures the freshness of the information of the source status at the destination. For any time that we do not have an update received at the destination, i.e. times that do not belong to the set $\mathcal{I} \doteq \{t_1', t_2', \ldots t_{N(\mathcal{T})}'\}$ the age increases as time passes by, leading to the sawtooth pattern of Figure 2.3.

2.2 Analysis of the Age of Information: The Basics

In the context we have been discussing so far, the objective of a communication system would be to maintain the information from the

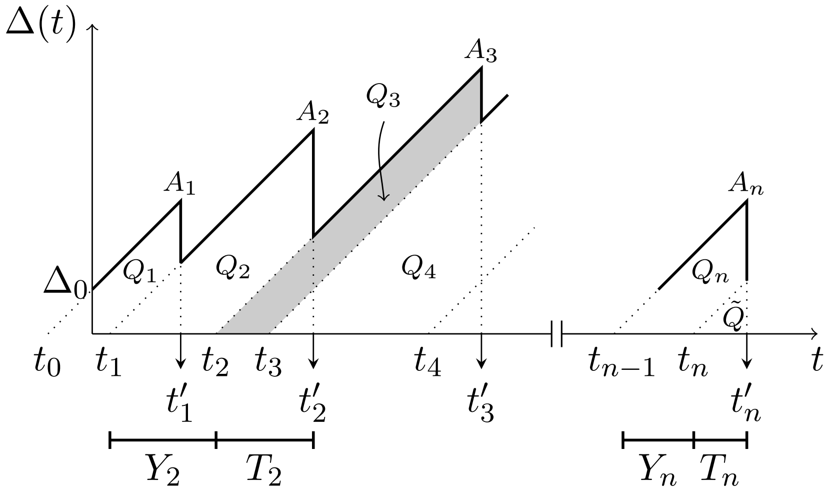

Figure 2.3: Example of the AoI evolution.

source as fresh as possible. As illustrated by the sawtooth pattern in Figure 2.3, the instantaneous age does not necessarily reflect timeliness. The maximum value of the AoI A_i immediately before an update is received, called PAoI, might be followed by either a small or a big reduction of AoI immediately after the update. The destination's requirement of timely updating then corresponds to small time average AoI. At the same time, a complete characterization of the AoI process follows from its stationary distribution that can lead to the derivation of higher order moments and alternative performance guarantees. In what follows, we begin with the definition of the time average AoI. Next, we consider a complete characterization of the AoI distribution, and finally, we present relevant performance metrics spawned by age.

2.2.1 Time Average Age

Given an age process $\Delta(t)$ and assuming ergodicity, the average age can be calculated using a sample average that converges to its corresponding stochastic average.

Definition 2 (Time average AoI)**.** *For an interval of observation $(0, \mathcal{T})$, the time average AoI of a status update system is*

$$\Delta_{\mathcal{T}} = \frac{1}{\mathcal{T}} \int_0^{\mathcal{T}} \Delta(t)\, dt. \tag{2.7}$$

The integral in (2.7) can be calculated as the area under $\Delta(t)$. The time average $\Delta_{\mathcal{T}}$ tends to the ensemble *average age* as $\mathcal{T} \to \infty$, i.e.,

$$\Delta = \lim_{\mathcal{T} \to \infty} \Delta_{\mathcal{T}}. \tag{2.8}$$

Furthermore, let

$$\lambda = \lim_{\mathcal{T} \to \infty} \frac{N(\mathcal{T})}{\mathcal{T}} \tag{2.9}$$

be the steady state rate of status updates generation.

After basic manipulations that utilize the disjoint areas Q_i, for $i \geq 1$, shown in Figure 2.3, the *average AoI* in the status update system of Figure 2.2 is given by

$$\Delta = \frac{\mathbb{E}[YT] + \mathbb{E}[Y^2]/2}{\mathbb{E}[Y]}, \tag{2.10}$$

where $\lambda = 1/\mathbb{E}[Y]$ and $\mathbb{E}[\cdot]$ is the expectation operator. This core methodological framework was built in [26]. Notice that ergodicity has been assumed for the stochastic process $\Delta(t)$ but no assumptions regarding the distribution of the random variables Y (interarrival time) and T (system time), have been made, nor any specific service policy has been considered. This result also holds when the system is shared among multiple traffic streams.

Moreover, observe that the random variables Y and T are dependent and this complicates the calculations of the average age in the general case, since we do not know their joint distribution. Intuitively, for a fixed service rate, reducing interarrival times correspond to packets filling up the system. This increased traffic leads to larger system times. On the other hand, larger interarrival times allow the queue to empty and consequently the delays are smaller. Thus, Y and T are negatively correlated, as illustrated in Figure 2.4.

To summarize, the AoI is determined by two factors (i) the processing/transmission delay that corresponds to the system time T and (ii) the pattern that the source uses to generate status updates. In Figure 2.5, we illustrate how Y and T impact AoI. In particular, we provide a numerical example of an M/M/1 queue with fixed service rate $\mu = 1$ and a variable arrival rate λ. Assuming the queue is stable, the arrival rate corresponds to the system throughput. Finally, recall that the average interarrival time $\mathbb{E}[Y]$ is inversely proportional to the arrival rate, i.e., $\lambda = 1/\mathbb{E}[Y]$. A small interarrival time leads to high average system time and average AoI. On the other hand,

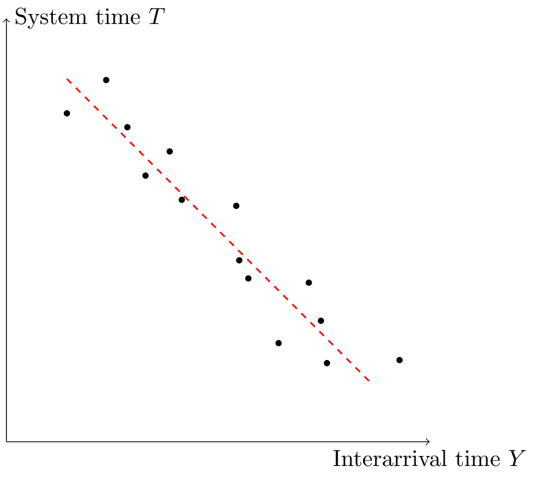

Figure 2.4: Y and T are negatively correlated.

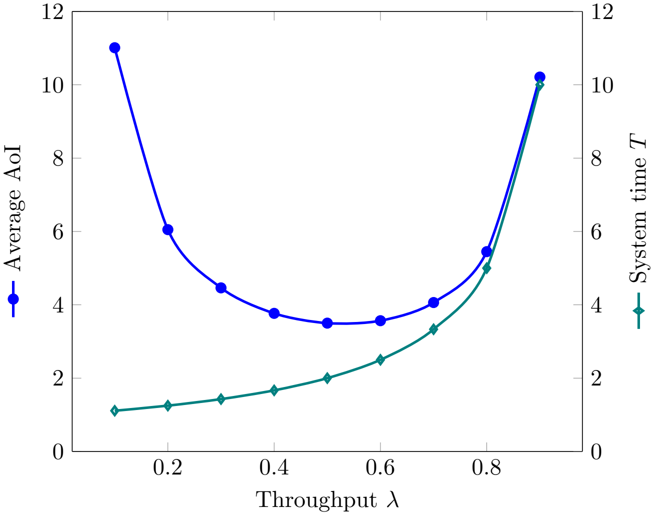

Figure 2.5: Average AoI, average throughput λ, and average system time T, for the M/M/1 queue with $\mu = 1$.

a large interarrival time leads to low average system time and high average AoI.

2.2.2 Stationary Distribution

In this section, we consider a complete characterization of the AoI distribution in a wide class of communication systems. To do that, we study a sample path of the AoI in order to have a deeper understanding of the underlying AoI properties under general assumptions. The presented approach was first developed in [39, 40].

Any sample path of the AoI process Δ_t can be constructed as follows. Let $\{t'_i, i \geq 0\}$ be a deterministic point process, with $t'_0 = 0$ and $t'_i < t'_{i+1} < \infty$. We interpret t'_i as the times at which the status updates are received at the destination. At time t, the number of events in $[0, t]$ is denoted by $N(t) = \max\{i : t'_i \leq t\}$, $t \geq 0$. We assume that $t'_i \to \infty$ as $i \to \infty$, so that there is a finite number of receptions in any finite time interval, and we note that, since $t'_i < \infty$ for all $i \geq 0$, we have that $N(t) \to \infty$ as $i \to \infty$. Associated with each point t'_i, the mark $T_i = \{\Delta_{t'_i}, i \geq 0\}$ denotes the value of AoI immediately after receiving the ith status update. Then, $\{(t'_i, T_i), i \geq 0\}$ denotes the marked point process of AoI on $[0, \infty) \times [0, \infty)$. The AoI process is non-negative, piece-wise non-decreasing, right-continuous, with discontinuous jumps at times t'_i. A sample path of the AoI process with an alternative representation is shown in Figure 2.6.

The AoI process Δ_t is thus determined completely by $\{(t'_i, T_i), i \geq 0\}$ as follows

$$\Delta_t = T_{i-1} + (t - t'_{i-1}), \quad t \in [t'_{i-1}, t'_i), \quad i \geq 1. \tag{2.11}$$

Definition 3 (Stationary distribution of the AoI)**.** *Consider a stationary, ergodic system. For an interval of observation* $(0, \mathcal{T})$*, the stationary distribution of the AoI is defined as the long-run fraction of time in which the AoI is less than or equal to an arbitrary fixed value* x*.*

$$\Delta(x) = \lim_{\mathcal{T} \to \infty} \frac{1}{\mathcal{T}} \sum_{t=0}^{\mathcal{T}} \mathbb{1}_{\{\Delta_t \leq x\}}, \quad x \geq 0. \tag{2.12}$$

The distribution in (2.12) can then be obtained in terms of the distributions of the system time T and the PAoI. This relation is of particular importance since it reduces the analysis of the AoI to the analysis of components that are easier to analyze. Moreover, following this approach we can derive the Laplace-Stieltjes transform (LST) or the moment generating function (MGF) of an AoI process. This allows the analysis of the mean and the higher order moments of the

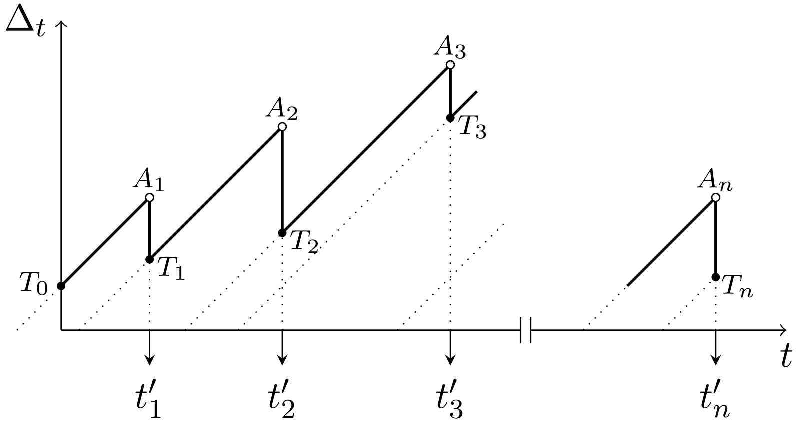

Figure 2.6: Alternative representation of a sample path of the AoI process.

age. This result is also particularly important in order to analyze non-linear functions of age.

In the current literature, there is a number of attempts addressing the AoI distribution. In [41] new tools such as stochastic hybrid systems (SHS) are developed to analyze AoI moments and the MGF of an AoI process in networks. In [40] a general formula of the stationary distribution of AoI is obtained and applied to a wide class of continuous-time single-server queues with different disciplines. The stationary distribution and the average performance analysis of non-linear information ageing, in discrete time, is studied in [42, 43]. The distribution of the AoI for the GI/GI/1/1 and GI/GI/1/2* systems, under non-preemptive scheduling is considered in [44]. In [45] the authors characterize the AoI distribution in bufferless systems. Delay and PAoI violation guarantees are studied in [46] for the reliable transmission of short packets over a wireless channel.

2.3 Relevant Metrics

The AoI metric can be modified to migrate to relevant performance metrics, different for each application. Examples of such alternative definitions, derived in relation to AoI, are summarized as follows. As we mentioned previously, the notion of PAoI was introduced in [27] as the value of the AoI immediately before an update is received. In fact, we will see that PAoI is not merely an alternative performance metric of the AoI but also an important part of unraveling AoI. In [33] the authors use AoII to extend the notion of fresh updates to that of fresh informative updates, that correspond to updates that bring new and correct information to the monitor side. The term effective age of information (EAoI) is used to represent the age of the information that is associated with decision-making [47]. Assuming that a general information source is represented as a continuous-time Markov chain, the authors in [48] analyze the effect of the AoI on the accuracy of a monitoring system. In [49, 50] effective age is loosely defined as an age-related metric that captures both the information structure of the signal and the sampling pattern that is used and is minimized when the error is minimized. In [51] the authors capture the freshness of status updates for different states of the observed stochastic process by introducing different AoI variables to account for the state changes. In [52] the term relative age of information (rAoI) is used to represent the AoI observed at the receiver relative to the AoI at the transmitter, in a point-to-point communication system. In [53] the instantaneous secrecy age is defined to characterize the secrecy performance of a status update system consisting of a legitimate receiver and an eavesdropper.

A noticeable part of relevant AoI metrics revolves around non-linear age functions and their applications. In practice, not all information sources vary in the same way over time. Consider for example the case of monitoring a remote surgery compared to the case of monitoring the temperature of a humidity sensor. In the former case, information changes more quickly with time. Therefore, the characteristics of the observed process at the source can play an important role in the chosen frequency of status update transmissions. In [54, 55] a so-called age penalty/utility function is employed to describe the level of dissatisfaction for having aged status updates at the destination. In [56] the authors use the mutual information between the real-time source value and the delivered samples at the receiver to quantify the freshness of the information contained in the delivered samples. A relationship between a non-linear function of the AoI and the estimation error of the Ornstein-Uhlenbeck (OU) process is investigated in [57]. In [28, 29] the CoUD metric is introduced to associate the cost of staleness with the statistics of the source. Furthermore, the VoIU is defined to capture the degree of importance of the information received at the destination.

The focus of this thesis is on the PAoI, the CoUD, and the VoIU metrics, hence in the next subsections we provide their formal definitions together with some insights.

2.3.1 Peak Age of Information

In addition to AoI, a metric called peak age is proposed to serve two objectives. First, depending on the application, it may be a suitable alternative to age and average age. Second, it is a more tractable solution in the analysis of complicated models. Consider the sawtooth pattern of the evolution of AoI over time, shown in Figure 2.3. Observing the peak values in the sawtooth curve we characterize the maximum value of the AoI immediately before an update is received called the PAoI [27]. The PAoI can be utilized in applications where there is interest in the worst case age or we need to apply a threshold restriction on age. This metric can be used instead of AoI, with the advantage of a simpler formulation.

Definition 4 (Peak age of information – PAoI)**.** *Let Y_i be the interarrival time of the ith update, and T_i be the corresponding system time. Then, the peak age of information (PAoI) metric is defined as the value of AoI achieved immediately before receiving the ith update*

$$A_i = Y_i + T_i. \tag{2.13}$$

Observe in Figure 2.3 the values of PAoI depicted with A_i and note that PAoI is a discrete stochastic process.

In analogy to the AoI, we are interested in small time average PAoI that corresponds to maintaining fresh information.

Definition 5 (Time average PAoI)**.** *Suppose that our interval of observation is $(0, \mathcal{T})$. The time average PAoI of a status update system is*

$$A = \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{i=1}^{N(\mathcal{T})} A_i, \tag{2.14}$$

where $N(\mathcal{T})$ is the number of samples which completed service by time $\mathcal{T}$.

In the status update system of Figure 2.2, where $\lambda = 1/\mathbb{E}[Y]$, the average PAoI is given by

$$A = \mathbb{E}[Y + T]. \tag{2.15}$$

This relation follows from the definition (2.13). Again, we assume ergodicity of the stochastic process $\Delta(t)$ but we make no assumptions regarding the distribution of the random variables Y and T, or any specific service policy. This result also holds when the system is shared among multiple traffic streams.

Comparing the average AoI in (2.10) and the average PAoI of (2.15), we have

$$\begin{aligned}\Delta - A &= \lambda\left(\mathbb{E}[YT] + \mathbb{E}[Y^2]/2 - \mathbb{E}[Y]\mathbb{E}[Y+T]\right)\\ &= \lambda\left(\mathbb{E}[YT] - \mathbb{E}[Y]\mathbb{E}[T] + \mathbb{E}[Y^2]/2 - \mathbb{E}[Y]^2\right). \end{aligned} \tag{2.16}$$

The difference in (2.16) is a way of estimating how close the two metrics are to each other. For deterministic interarrival times $\mathbb{E}[Y] = D$ equation (2.16) yields $\Delta = A - \lambda Y^2/2$. Therefore, PAoI serves as an upper bound for AoI.

2.3.2 Cost of Update Delay

As we outlined at the beginning of this section, it is meaningful to capture the information characteristics of the source by modifying the definition of AoI to a non-linear cost function. The aim is to penalize the absence of updates at the destination according to the source characteristics by a non-negative, monotonically increasing category of functions. Hence, we expand the concept of information ageing by introducing the CoUD [29] metric to characterize the cost of having stale information at the destination. Age penalty functions of a general form were first defined in [30], to characterize the level of "dissatisfaction" for data staleness. In this thesis, we are going to investigate the CoUD metric for three sample case functions.

The need to go beyond AoI can be associated with the application as well as with the statistics of the source. Before defining this association, we first need to elaborate on the requirement of small AoI. Let us go back to consider why we are interested in small AoI. Consider that we are observing a system at time instant t. However, the most recent value of the observed process $X(t)$ available is the one that had arrived at $t - \Delta$, for some random Δ. Now assume that the destination node wants to estimate the information at time t. If the samples at t and $t - \Delta$ are independent, the knowledge of $t - \Delta$ is not useful for the estimation and age simply indicates delay. However, if the samples at t and $t - \Delta$ are dependent, then the value of Δ will affect the accuracy of the estimation. A smaller Δ can lead to a more accurate estimation.

Definition 6 (Cost of update delay – CoUD)**.** *Consider a system consisting of a source-destination communication pair. Assume the most recently received update at the destination at time t carries a timestamp of its generation $u(t)$. Then, the cost of update delay (CoUD) metric is defined as a random process*

$$C(t) = f_s(t - u(t)), \tag{2.17}$$

where $f_s(\cdot)$ denotes a non-negative, monotonically increasing function.

The function $f_s(\cdot)$ represents the evolution of CoUD according to the data characteristics of the source. Note that age, as coined by Kaul et al. [26], is a special cost case, where the cost is counted in time units, as shown in Figure 2.3. As a generalization, we consider that the cost can take any form of a "payment" function that can have any relevant unit. The selection of the $f_s(\cdot)$ function of CoUD according to the autocorrelation of the observed process is proposed in [29].

In analogy to the AoI, keeping the average CoUD of a system small corresponds to maintaining freshness. Given the process $C(t)$ and assuming ergodicity, the average CoUD can be calculated using a sample average that converges to its corresponding stochastic average.

Definition 7 (Time average CoUD)**.** *Suppose that our interval of observation is $(0, \mathcal{T})$. The time average CoUD of a status update system is*

$$C = \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \int_0^{\mathcal{T}} C(t)\, dt. \tag{2.18}$$

The integration in (2.18) can be calculated as the area under the sawtooth of $C(t)$.

2.3.3 Value of Information of Update

At the destination, the timeliness of the available information can also be characterized by VoIU which is an alternative metric to the AoI and CoUD. To that extend, we introduce the VoIU metric that captures the reduction of CoUD upon reception of an update [29].

In other words, the VoIU captures the degree of importance of the status update received at the destination. A newly received update reduces the uncertainty of the destination about the current value of the observed stochastic process $X(t)$, and VoIU captures that reduction that is directly related to the time elapsed since the last update reception. Following this approach, we take into consideration the probability of a reception event, and the impact of the event on our knowledge of the evolution of the process.

Definition 8 (Value of information of update – VoIU)**.** *Consider a system consisting of a source-destination communication pair. Update i is generated at time t_i and is received by the destination at time t'_i. At time t'_i, the cost $C(t'_i)$ is reset to $f_s(t'_i - t_i)$ and the value of information of update (VoIU) i is defined as*

$$V_i = \frac{f_s(t'_i - t_{i-1}) - f_{s_i}(t'_i - t_i)}{f_s(t'_i - t_{i-1})}, \tag{2.19}$$

to measure the degree of importance of the information received at the destination. Note that, $f_s(\cdot)$ represents a non-negative, monotonically increasing category of functions.

The VoIU is a bounded fraction that takes values in the interval $[0, 1]$, with 0 representing the minimum value of an update and 1 the maximum. When the interarrival time of updates grows to infinity, the VoIU takes its maximum value, since it becomes extremely useful to receive an update. On the other hand, when the system time gets significantly large we expect that the received update is not as timely as we would prefer in order to maintain the freshness of the system, hence the VoIU metric gets its minimum value.

Depending on the application we can either choose to minimize the average CoUD of a system or to maximize the average VoIU. Given the process $C(t)$ and assuming ergodicity, the average VoIU can be calculated using a sample average that converges to its corresponding stochastic average.

Definition 9 (Time average VoIU)**.** *Suppose that our interval of observation is $(0, \mathcal{T})$. The time average VoIU of a status update system is*

$$V = \lim_{\mathcal{T}\to\infty} \frac{1}{\mathcal{T}} \sum_{i=1}^{N(\mathcal{T})} V_i, \tag{2.20}$$

where $N(\mathcal{T})$ *is the number of samples which completed service by time* $\mathcal{T}$*.*

Small CoUD corresponds to timely information while VoIU represents the impact of the received information in reducing the CoUD. Therefore, in a communication system it would be desirable to maximize the average VoIU.

Chapter 3

System Setups and Solution Tools

The AoI literature has addressed system setups of multiple components and design targets. In addition to that, different analytical tools can be utilized to cope with the challenges that the AoI problems encounter. In this chapter, we focus on different aspects of the AoI-problem modeling and tackling. In addition, we present applications of the notion of AoI in different areas.

3.1 Queue-theoretic Modeling Frameworks

The first attempts to address the AoI of a source at the destination of a status update transmission system were made through simple queueing models. The analysis of delay using queueing theory is a widely used methodology that provides a mathematical analysis of systems with probabilistic events. Different queueing disciplines and features have been considered, where the main key characteristics to be determined are (i) the number of sources (ii) the arrival process distribution (iii) the queue discipline (iv) the number of servers (v) the service process distribution.

In [26] three simple models are studied, the M/M/1, the M/D/1, and the D/M/1, under the first-come-first-served (FCFS) discipline. The main result of this seminal work is the observation that optimizing the timeliness of status updates through the AoI results in a queue policy that was controversial up to that point. Specifically, in the M/M/1 case, keeping the server idle $\approx 47\%$ of the time is optimal with respect to the AoI metric. An expansion of the basic model in Figure 2.2 that includes multiple sources sharing a common queue is studied in [58, 59, 60, 61]. The analysis therein illustrated how combining multiple sources in a common queue is more efficient in terms of the average AoI of each source, than serving them separately.

Moving to different system characteristics, in [62] the authors consider systems with different availabilities of resources (servers). Under this assumption, a more dynamic feature of networks is considered, that is, packets traveling over a network might reach the destination through numerous alternative paths thus the delay of each packet might differ. In this context, the performance of the M/M/1, M/M/2, and M/M/∞ queues is provided and the tradeoff between AoI and the waste of network resources as the number of servers varies is demonstrated. Minimizing AoI in multi-server systems over the space of update generation and service time distributions is studied in [63].

Two efficient ways to avoid congestion in networks are packet management techniques and flow control, since they can manipulate the traffic entering the network. Packet management by dropping or replacing packets is investigated in [27, 64] where the M/M/1/1, M/M/1/2, and M/M/1/2* queues are considered. The AoI in a discrete time queueing system with and without packet management at the transmission queue of the source node is derived in [65]. A key outcome is that packet management can reduce the delay imposed to packets due to the waiting time in the queue and therefore improve the performance of the system with respect to the staleness of the transmitted information. Multiaccess strategies with packet management in a network with multiple source nodes transmitting to a common receiver are studied in [66]. More general systems such as the G/G/1/1 under two service discipline models are considered in [67].

Another approach of controlling packets is by utilizing the last-come-first-served (LCFS) queue discipline. In addition, a system can support the preemption of updates in service by prioritizing new arrivals to the packets receiving service. Allowing newly generated status updates to surpass older status updates, with and without the use of preemption, is studied in [68, 69, 70, 60]. The difficulty of extending the traditional queueing theory analysis to analyzing multi-hop, multi-server systems has led [41] to propose an SHS approach to analyze AoI moments and the MGF of an AoI process in networks. Average age for a series of LCFS queues in tandem is analyzed in [71, 72]. The AoI of data streams with different priorities is investigated in [73, 74].

3.2 Optimization and Control

A variety of optimization tools and algorithm designs have been proposed and studied for the AoI minimization problem. Depending on the characteristics of the system and the available means to control it, there is a potential to introduce new models capturing the communication medium and different mechanisms that control different parts of the system.

Assuming perfect knowledge of the server state, the authors in [54] look at the optimal rate control policy at the transmitter and illustrate when it is preferable to wait for a certain amount of time before generating a new update, instead of generating an update as soon as the previous update finishes service [75]. The problem of identifying the optimal sampling strategy of a communication system in relation to AoI, has attracted particular attention due to the connection it implies with estimation errors [76, 77, 78, 79]. In [80] the authors formulate a dynamic programming problem and utilize the framework of Markov decision processes (MDP) to study the interaction of heterogeneous traffic flows in a shared queue.

Link scheduling is a fundamental problem in wireless communications, widely studied in the context of access coordination. A subproblem of it, the so-called link activation problem, aims to determine links that can be simultaneously active in a shared channel under some performance requirements. The optimal scheduling policy is usually governed by an objective related to some cost criterion and complexity considerations. The most common performance objectives have been those of the maximum throughput or the minimum completion time/delay for all the links.

The notion of AoI opens a new research direction for optimal scheduling, in particular because minimization of the completion time leads, in general, to suboptimal solutions in terms of AoI. The authors of [81] propose a novel approach of optimizing the transmission scheduling of source-destination links with respect to age. The task is to solve a minimum age scheduling problem (MASP), for which a schedule consists of activation of link subsets and the sequence of the activations. In addition to proving the NP-hardness of MASP, an integer linear programming (ILP) is provided for performance benchmarking. A similar problem is studied in [82]. There, the objective is to minimize the maximum PAoI, to address both information freshness and fairness among the sources.

The work in [83] considers scheduled access and slotted ALOHA-like random access in a simple system setup. Under scheduled access, the nodes take turns and they get feedback on whether a transmitted packet is received successfully by the sink. A node may transmit more than once to overcome channel uncertainty. For the slotted ALOHA-like access scheme, each node attempts to transmit in every slot with a given probability. For the scheduled access and the slotted ALOHA-like schemes the AoI is derived.

In [20] a broadcast network where many users are interested in different pieces of information that should be delivered by a base station is considered. The paper focuses on the long-run average AoI and shows that an optimal scheduling algorithm is a simple stationary switch-type. That is, given the age of all other users, an optimal decision for a user is based on an age threshold. The authors leverage an infinite state Markov decision process; however considering practical cases, a sequence of finite state approximations is proposed and shown to converge. An optimal offline and an online scheduling algorithm are given; the latter does not require arrival statistics for the problem setup investigated.

The authors in [19] consider an unreliable broadcast network, where a base station sends updates to a set of clients and formulate a discrete-time decision problem to find a scheduling policy that minimizes the expected weighted sum AoI of the clients in the network. Results presented show that a Greedy Policy, which transmits the packet with the highest current age, is optimal for the case of symmetric networks.

In [84] the authors outline the inefficiency of conventional approaches in maintaining fresh information updates of multiple continuous flows, and show the critical value of both age and interarrival times. They develop a new scheduler, which can operate regardless of the knowledge of arrival rates, and accounts for both age and interarrival times of incoming packets. Upper and lower AoI performance bounds are provided. Analytical results are obtained for heavy-traffic conditions, however, numerical outcomes also support the proposed scheduler even in lightly-loaded conditions.

More recent works [85, 86, 87, 88, 89, 90, 91] propose centralized and decentralized scheduling policies for AoI minimization, under general interference constraints and time varying channels. The proposed scheduling algorithms have low complexity with strong AoI performances over stochastic information arrivals.

Tools from Lyapunov optimization theory have been utilized to address stochastic network optimization problems related to AoI. In [92] the authors consider both transmission and sampling costs in a wireless network with time average AoI constraints. Joint optimization of the transmit power allocation, subchannel assignment, and sampling action with constrained AoI in a wireless network is studied in [93]. To solve the optimization problem, the authors use the Lyapunov drift-plus-penalty method and provide an algorithm that minimizes the power consumption while keeping the data at the destination fresh. Moreover, some works consider optimal control policies of status updates in a multiple access channel with stability constraints [94] and throughput constraints [88].

Furthermore, a diversity of additional features of a communication system have been studied in relation to AoI. Among these features, imperfect packet transmission has been considered in the context of a hybrid automatic repeat request (HARQ) mechanism [95, 96, 97] and a data protection scheme [98, 99]. In [100] a packet management mechanism that controls packets by attaching a deadline constraint to them is proposed. In [101] the distribution of the AoI is characterized in a system with packet deadlines and infinite buffer capacity. Minimizing the AoI in multi-hop networks is studied in [102, 103, 104]. The AoI performance in large networks with multiple source-destination pairs are studied in [105, 106]. Source and channel coding aspects can be found in [107, 108, 109, 110].

3.3 Applications

Departing from the basic characterizations and the early modeling aspects, AoI can be treated as a tool to address different application areas. Since the notion of AoI has started evolving, there is a growing body of literature that studies its application as a tool. This new concept can be applied towards achieving a wide range of objectives in communication systems that deal with time critical information while having limited resources.

An important aspect of communication systems is energy replenishment and the *energy harvesting* capability in which wireless devices (such as sensor nodes) may rely on. The time-varying availability of energy and battery constraints at the transmitter can limit the sampling rate on the transmission end. Therefore, it is of high interest to investigate how a stochastic energy harvesting system affects the AoI at the destination and to find the optimal policy.

The minimization of AoI under such considerations was first studied in [111]. Consider the energy harvesting process $H(t)$ as the total energy harvested over time $[0, t]$. The number of status updates that can be served depends on $H(t)$. In the continuous time setup of the problem, the sequence of the extracted samples (i.e. status updates) should be selected to minimize the energy-constrained average AoI. The discrete time setup of the problem accounts for the state of the source that is either busy or idle, hence we have a binary decision problem at each time slot. Apart from the stochastic energy arrival process, another difference of this work compared to previous studies is the assumption of instant transmission of packets. In this setup, the authors derive an offline solution that minimizes the time average AoI for an arbitrary energy replenishment profile, using a discrete time dynamic programming formulation. It is also found that the expected value of the current age as well as the current energy level at the transmitter is sufficient information to generate an optimal threshold policy. An effective online heuristic, named balance updating (BU), achieving performance close to an offline policy is also proposed. Simulations of the policies indicate that they can significantly improve the age over greedy approaches.

Energy harvesting constraints are also considered in [75], where in contrast to [111] the randomness is on the service times and not on the energy arrival process. A complete representation of an energy harvesting system with a minimum AoI objective would include the age process $\Delta(t)$, the available energy at the source $H(t) - U(t)$, where $U(t)$ is the energy consumption process, and the energy harvesting process $H(t)$. An optimal rate control policy would use this information to make the optimal decisions on the interarrival times of status updates. Such policies can be complex, even under simple harvesting assumptions. However, under the ergodicity assumption for the energy harvesting process, follows a simpler approach that uses averaging [75]. Managing the average energy consumption can be sufficient since a sufficiently large battery removes the need for precise energy management.

A number of works considering AoI and energy harvesting have followed. Indicatively, the authors in [112, 113, 114] address the continuous time problem of optimizing when status updates should take place in a real-time remote sensing scenario with a sensor which is restricted by time-varying energy constraints and battery limitations. In [115], considering two energy arrival models, the random battery recharge (RBR) model and the incremental battery recharge (IBR) model, an optimal energy-dependent threshold policy is provided. In [116] the problem of finding a policy for generating updates from a source with finite battery, that achieves the lowest possible time-average expected age penalty among all online policies is considered.

In cellular networks, each base station (BS) needs to estimate the channel responses from the user equipments (UEs) that are active in the current coherence block. The channel responses are utilized by the BS to process the uplink and downlink signals. In practice, these values need to be estimated regularly thus, they add a non-negligible overhead to the system. The knowledge of the current channel response realizations is the *channel state information* (CSI). If the uplink and downlink are separated in frequency, for example using a frequency division duplex (FDD) protocol, i.e. the respective channels are different, we cannot rely on reciprocity.

In non-reciprocal wireless links, the transmitter knows the current channel state through the CSI feedback sent from the receiver. In this case, the available information at the destination has aged over time, affecting the efficiency of the communication. The channel information ageing is caused by multiple factors such as (i) measuring times, (ii) transmission delay, (iii) processing time required to decode and estimate the channel quality, (iv) processing time to run adaptation functions, (v) frame times, and (vi) the interval between consecutive reports from the UE. In [117] and [118] the factors (i)-(v) are collectively represented by a random variable that captures the time elapsed from the generation up to the reception of the CSI. Factor (vi) is denoted by τ. The case of deterministic τ corresponds to a system with periodic feedback, while the case of random τ corresponds to a system with aperiodic feedback. In current standards such as Long Term Evolution (LTE) both feedback modes are supported [119].

Applying this setup to the AoI framework discussed previously we are interested in the effect of outdated CSI on the performance of feedback links and protocols. In [117] and [118] utility functions are used as a general performance metric that accounts for various scenarios and includes the cost of feedback. Thus, the tradeoff between utility and frequency of reports can be characterized. As a first step, the channel in these works is modeled as a finite state Markov channel (FSMC) with two states representing the fading conditions, one "good" and one "bad", yielding tractable analytic results. Details regarding the probability of error on channel estimation and the proposed utility functions can be found in [117] and [118]. Finally, the work in [120] considers theoretical bounds and protocols to estimate and disseminate the global CSI in wireless networks with reciprocal channels.

Another immediately promising area for research lies in *caching* and content placement in general. There have been a number of works on caching policies aiming to minimizing cache misses [9] using the request rates and popularity, together with content age, and updating dynamic content in a cache in order to minimize the average age of cached items [10, 121]. Caching of messages has become of critical importance due to the pervasiveness of highly demanding online services (such as online gaming, video on demand, and augmented reality applications) and the IoT. Overall, there is an immense wealth of possible application domains associated with the notion of timeliness as captured by age.

Chapter 4

Contributions of the Thesis

This thesis aims at modeling and analyzing information-freshness aware communication systems. Our contributions consist of results derived through mathematical analysis and simulations that study the AoI in relation to other performance metrics, in various multiple access and point-to-point communication setups. The results highlight the characteristics of the AoI as a performance metric and provide guidelines for the design of systems with heterogeneous data traffic. The heterogeneity of the data traffic is captured in two different ways. First, by considering different objectives such as the AoI, the PAoI, the CoUD, the VoIU, or the throughput associated with the source nodes. Second, by allowing or not packets to be dropped from the system depending on the application. Using rigorous analysis, this thesis explores fundamental properties of information freshness as captured by the AoI metric.

The thesis consists of four research papers. In these papers, the main ideas are the result of discussions among all authors. The author of this dissertation has contributed to Papers I-IV as the first author working on the development of the model formulations, the theoretical analysis and implementation of algorithms, the simulation and numerical results along with the writing of the papers. The papers and the main scientific contributions are summarized in the following.

4.1 Publications Included in the Thesis

Paper I: Age of Information and Throughput in a Shared Access Network with Heterogeneous Traffic, co-authored with N. Pappas, A. Ephremides, and V. Angelakis. This paper has been published in *Proc. of IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6, December 2018.

In this work, we consider a cognitive shared access network consisting of a high priority primary node and a low priority network with N secondary nodes accessing the spectrum. The primary node has a buffer of infinite capacity to store the incoming bursty traffic in the form of packets and the queues at the secondary nodes are assumed to be saturated. The nodes attempt to access the spectrum with given probabilities and the receivers are assumed to have multipacket reception (MPR) capabilities. The wireless channel is modeled as Rayleigh fading channel with additive white Gaussian noise.

We consider two performance metrics. The AoI of the primary node at the receiver, that quantifies the freshness of the knowledge the receiver has about the status of the primary node. In addition, the secondary nodes are interested in maximizing their throughput that corresponds to the maximum service rate in packets/slot. We derive rigorous analytical expressions of the time average AoI of the primary node and the throughput of the secondary nodes. Then, we formulate two optimization problems, the first aiming to minimize the time average AoI of the primary node subject to an aggregate secondary throughput requirement. The second problem aims to maximize the aggregate secondary throughput of the network subject to a maximum time average staleness constraint. Either one of the problems can be used depending on the application and provides new insights into utilizing AoI in such systems.

The AoI is shown to be a monotonic function of the access probabilities of the primary and secondary nodes. The conditions that guarantee the stability of the primary queue also determine the feasibility region of AoI. Moreover, we observe that there is an optimum number of users N^* that maximizes the aggregate secondary throughput and depends on the secondary access probabilities. Our results illustrate the impact of the system parameters on the performance and indicate that there is an optimum system-dependent arrival rate λ at the primary node that leads to the largest feasible region of

(N, λ). The rate that maximizes the feasible region (N, λ) is not necessarily optimal with respect to the two performance objectives of the network.

Paper II: Age of Information Performance of Multiaccess Strategies with Packet Management, co-authored with N. Pappas, A. Ephremides, and V. Angelakis. This paper has been published in *IEEE/KICS Journal of Communications and Networks (JCN) Special Issue on Age of Information*, vol. 21, no. 3, pp. 244-255, June 2019.

In this work, we consider a network consisting of multiple source nodes communicating with a common receiver. Each source node has a buffer of infinite capacity to store incoming bursty traffic in the form of packets which should keep the receiver timely updated. These packets are sent through wireless channels to an access point (AP) and then from the AP they are transmitted through an error-free network to the final destination.

Under this setup, we propose two different queue disciplines, without and with packet management. The first, assumes that all packets need to be delivered to the destination regardless of the freshness of the status update information. The second discipline assumes that newly arriving packets can replace older ones that are waiting in the queue for transmission. In addition, we renew the classical problem of multiple access in wireless networks by utilizing an AoI performance objective. Packets depart from the queues either in a perfectly scheduled or a random fashion. We consider three different policies to access the common medium (i) round-robin scheduler (ii) work-conserving scheduler (iii) random access.

We investigate the AoI performance of the network for the proposed multiple access policies, including scheduling and random access. The results highlight the performance gains of the work-conserving scheduler compared to the round-robin scheduler that come with higher coordination requirements. For the case of the random access one should optimize the access probabilities in connection to the arrival rates per source and the number of source nodes in the system. We present a rigorous analysis of the time average AoI with and without packet management at the transmission queue of the source nodes. Furthermore, we incorporate the effect of channel fading and network path diversity in such a system and provide simulation results that illustrate the impact of the network operating parameters on the performance of the different access protocols.

Parts of the paper were accepted for publication and presented in the following conference:

- A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, "Queue Management for Age Sensitive Status Updates," in *Proc. IEEE International Symposium on Information Theory (ISIT)*, pp. 330-334, July 2019.

Paper III: The Cost of Delay in Status Updates and their Value: Nonlinear Ageing, co-authored with N. Pappas, A. Ephremides, and V. Angelakis. This paper is accepted for publication in *IEEE Transactions on Communications*, April 2020.

In this work, we consider a real-time status update system consisting of a source-destination link. A stochastic process is observed at the source, and samples, so-called status updates, are extracted at random time instances, and delivered to the destination. Aiming to expand the concept of information ageing we introduce the CoUD metric to provide a flexible measure of having stale information at the system destination. Specifically, we investigate the CoUD metric for three sample case functions, the linear, the exponential, and the logarithmic, that can be easily tuned through a parameter. We propose the association of these functions with the statistics of the source.

Furthermore, we introduce the VoIU metric that captures the reduction of CoUD upon reception of an update. Small CoUD corresponds to timely information while VoIU represents the impact of the received information in reducing the CoUD. Therefore, in a communication system it would be highly desirable to minimize the average CoUD, and maximize the average VoIU. To this end, we obtain the average CoUD and VoIU for a system modeled as an M/M/1 queue with an FCFS discipline and discuss the optimal server utilization policy with respect to each one of them, and their relation. In addition, we derive upper bounds to the average CoUD that may be used for further system design and optimization, and we establish their association with the by-product of CoUD, called, peak cost of update delay (PCoUD). The flexibility of these notions enables their potential usage to establish differentiated service classes in status update systems.

We analyze the relation between CoUD and VoIU and observe that convex and concave CoUD functions lead to a tradeoff between CoUD and VoIU, while linearity reflects only on the CoUD. Depending on the application we can choose the utilization that satisfies the minimum CoUD objective or the maximum VoIU objective. In the linear CoUD case, VoIU is independent of the cost assigned per time unit. In the exponential and logarithmic cases however, there is a tradeoff between CoUD and VoIU. That is, the smaller the average CoUD, the smaller the average VoIU. For high correlation among the source samples, choosing a logarithmic function decreases their value of information and equivalently choosing an exponential function in low correlation has the opposite effect.

Parts of the paper were accepted for publication and presented in the following conference:

- A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, "Age and Value of Information: Non-linear Age Case," in *Proc. IEEE International Symposium on Information Theory (ISIT)*, pp. 326-330, June 2017.

Paper IV: The Age of Information in a Discrete Time Queue: Stationary Distribution and Non-linear Age Mean Analysis, co-authored with N. Pappas, A. Ephremides, and V. Angelakis. This paper is under submission to *IEEE Journal on Selected Areas in Communications (JSAC) Special Issue on Age of Information in Real-time Systems and Networks*, May 2020.

In this work, we investigate information freshness in a status update communication system consisting of a source-destination link. Initially, we study the properties of a sample path of the AoI process at the destination. We obtain a general formula of the stationary distribution of the AoI, under the assumption of ergodicity. We relate this result to a discrete time queueing system and provide a general expression of the generating function of AoI in relation with the system time and the PAoI. This novel approach starts with few assumptions and invokes more assumptions that narrow down the considered system. The fewer the assumptions, the more general the results.

Furthermore, we consider three different single-server system models and we obtain closed-form expressions of the generating functions and the stationary distributions of the AoI and the PAoI. The first model is an FCFS queue, the second model is a preemptive LCFS queue, and the last model is a bufferless system with packet dropping. These results can be utilized to provide AoI and PAoI performance guarantees, in terms of violation probabilities. Moreover, for all models, we investigate the optimal arrival probability at the source node that minimizes AoI, and show the fundamental differences of the proposed models.

We build upon these results to provide a methodology for analyzing general non-linear age functions for this type of systems. To this end, we provide a convenient way to determine the time average PCoUD and CoUD by representing functions with power series. A proposed algorithm provides guidelines for the time average performance analysis of functions that can be represented as power series. Our results are general enough to be utilized to a variety of settings in terms of the queueing discipline, the arrival and service process, and the non-linear cost function at the destination.

Parts of the paper were accepted for publication in the following conference:

- A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, "Non-linear Age of Information in a Discrete Time Queue: Stationary Distribution and Average Performance Analysis, " accepted in *Proc. IEEE International Conference on Communications (ICC)*, June 2020.

4.2 Publication not Included in the Thesis

Monograph: Age of Information: A New Concept, Metric, and Tool, co-authored with N. Pappas and V. Angelakis. Published in *Foundations and Trends® in Networking*, vol. 12, no. 3, pp. 162 – 259, November 2017.

Abstract: Age of information (AoI) was introduced in the early 2010s as a notion to characterize the freshness of the knowledge a system has about a process observed remotely. AoI was shown to be a fundamentally novel metric of timeliness, significantly different, to existing ones such as delay and latency. The importance of such a tool is paramount, especially in contexts other than transport of information, since communication takes place also to control, or to compute, or to infer, and not just to reproduce messages of a source. This volume comes to present and discuss the first body of works on

AoI and discuss future directions that could yield more challenging and interesting research.

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Part II

Papers

Papers

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