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Age of Information in Satellite Networks

Master Candidate

Fabio Kastrati

Student ID 2050786

Supervisor

Leonardo Badia

University of Padova

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To my mother Aida, thank you for being the best mother anyone could ask for. Even if at some point I stop doing things for myself, I continue because of you, so I can make you proud and offer you the life and happiness you deserve. You are my source of motivation and I cannot put into words how much I love you.

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To the rest of family and friends, don't get mad you weren't included, but as a social butterfly, this section would be longer than the thesis if I went one by one. You all have a special place in my heart and you know who you are, as I never spare words of appreciation.

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Contents

List of Figures

List of Acronyms

AoI Age of Information

LEO Low Earth Orbit

HAP High-Altitude Platform

IoT Internet of Things

ML Machine Learning

NASA National Aeronautics and Space Administration

Handover The process of transferring communication from one satellite or station to another

Starlink Satellite internet constellation operated by SpaceX

OneWeb Satellite internet constellation providing global broadband services

Project Loon Former Google initiative using balloons to provide Internet access in remote areas

IEEE Institute of Electrical and Electronics Engineers

Abstract

This thesis focuses on optimizing the Age of Information (AoI) in Low Earth Orbit (LEO) satellite networks, where maintaining data freshness is crucial for real-time communication systems. With increasing reliance on satellite constellations for global communication services such as Internet access and disaster monitoring, minimizing AoI has become a key performance objective.

The research proposes a framework that integrates predictive scheduling, multi-satellite cooperation, and energy-aware algorithms to optimize AoI in LEO satellite networks. Predictive scheduling leverages satellite trajectory data to forecast handovers and schedule updates at optimal times, while energy-aware algorithms adjust update frequency based on available energy. Multi-satellite cooperation is introduced to distribute communication tasks across satellites, reducing redundancy and improving network efficiency.

The key findings of the research demonstrate that predictive scheduling significantly reduces AoI spikes by transmitting updates before satellite handovers, ensuring that real-time data is maintained across the network. Multi-satellite cooperation enhances communication efficiency by allowing satellites to coordinate transmissions and share resources, resulting in lower AoI and optimized energy consumption. Energy-aware algorithms ensure that satellites manage their limited energy resources efficiently, balancing the trade-off between frequent updates and energy conservation.

The findings are particularly relevant for large satellite constellations, such as Starlink and OneWeb, which aim to provide global Internet services with low latency. Additionally, the research has significant implications for disaster monitoring systems and other real-time applications where maintaining up-to-date information is critical.

In conclusion, this thesis demonstrates the importance of AoI optimization in satellite networks and provides a robust framework for improving communication efficiency while ensuring real-time data availability, making it a critical consideration for future satellite communication systems.

1 Introduction

1.1 Background

The rapid advancements in satellite networks [22], particularly within *Low Earth Orbit (LEO)* [41], have paved the way for real-time global communication and data transfer. These networks, exemplified by major initiatives like *SpaceX's Starlink* [43] and *Amazon's Project Kuiper* [6], consist of vast constellations of satellites that orbit the Earth at altitudes between 500 km and 1,200 km. Due to their relatively low altitude, LEO satellites are capable of delivering low-latency communication, making them suitable for applications such as *broadband internet*, *remote sensing* [15], *disaster monitoring*, and the increasingly prominent *Internet of Things (IoT)* [11] networks.

Nevertheless, the dynamic nature of LEO satellite systems, where satellites are constantly orbiting and handing off communication between ground stations, presents unique challenges in ensuring that the information received remains *fresh* and up-to-date. This challenge brings to the forefront a key performance metric known as the *Age of Information (AoI)* [46], which serves as a measure of how current the data received by a destination is.

The concept of *AoI* was initially introduced by Roy D. Yates and collaborators in their seminal work titled *"Age of Information: An Introduction and Survey"*. Unlike more traditional network performance metrics such as latency or throughput [12], AoI directly measures the time elapsed since the most recent update was received, offering a precise indication of whether the data is current or outdated. As LEO satellite networks are increasingly relied upon for real-time applications, reducing AoI has become a fundamental objective to ensure the freshness and accuracy of transmitted data.

LEO satellite networks face specific challenges due to their inherent characteristics, including:

- **Frequent handovers**: As LEO satellites rapidly traverse the sky, ground stations must frequently hand off communication between satellites. These handover processes can result in delays [8], leading to an increase in AoI.
- **Energy constraints**: LEO satellites are typically powered by limited energy sources, often relying on solar panels and battery storage. Any strategies aimed at minimizing AoI must also consider energy usage to avoid exhausting critical resources.

In this thesis, we aim to develop and explore *mathematical models* and *optimization techniques* [17] designed to minimize AoI in LEO satellite networks. By analyzing state-of-the-art methods and proposing novel scheduling algorithms, this work seeks to enhance the efficiency of LEO satellite constellations, particularly in applications where timely and reliable data transmission is critical, such as disaster monitoring and IoT communications.

1.2 Problem Statement

As LEO satellite constellations continue to expand, the task of ensuring that the data transmitted remains fresh and relevant becomes increasingly difficult. The central challenge is optimizing the Age of Information (AoI) within these dynamic satellite networks, which are characterized by intermittent connectivity and constrained energy resources. Without efficient scheduling mechanisms in place, high AoI can result in the reception of outdated information, which can severely impact critical real-time applications such as *navigation systems*, *environmental monitoring*, and *emergency response operations* [18].

This thesis seeks to answer the following key question: *How can we develop effective scheduling algorithms to minimize AoI in LEO satellite networks, while simultaneously managing energy constraints and enhancing handover efficiency?*

1.3 Research Objectives

The primary goals of this thesis are as follows:

1. To thoroughly review and analyze existing methods for calculating and minimizing AoI, with a particular focus on their application in non-terrestrial networks like LEO constellations.

2. To develop *energy-aware scheduling algorithms* that not only aim to minimize AoI but also maintain a balance with energy efficiency.

3. To design and implement a *predictive scheduling algorithm* capable of anticipating satellite handovers, thereby optimizing AoI in a constantly shifting network environment.

4. To simulate various scheduling strategies and compare their performance in terms of *AoI*, *energy consumption*, and *communication latency*.

1.4 Thesis Structure

This thesis is organized into the following chapters:

- **Chapter 2: Literature Review** discusses prior research on Age of Information (AoI), exploring its theoretical foundations, applications in satellite networks, and the impact of energy constraints on optimizing AoI.

- **Chapter 3: Methodology** explains the mathematical models and scheduling algorithms developed to minimize AoI, along with the simulation framework used to evaluate their effectiveness.

- **Chapter 4: Results and Analysis** evaluates the performance of the proposed scheduling strategies, analyzing their impact on AoI, energy consumption, and communication efficiency.

- **Chapter 5: Conclusion** summarizes the main contributions and findings of this research and proposes future directions for improving AoI in satellite communication networks.

2

Literature Review

2.1 Theoretical Foundations of Age of Information (AoI)

The concept of *Age of Information* (AoI) has emerged as a critical metric in modern communication networks, offering a novel way to evaluate data freshness. Initially introduced by Yates et al . (2012), AoI provides a shift in focus from traditional performance metrics like **latency** and **throughput**, which primarily measure transmission delays or the amount of data transferred. Instead, AoI focuses on a more refined aspecttracking how recently the data was generated or updated. In systems where real-time decision-making depends on up-to-date information, such as satellite communications, the freshness of data becomes crucial, making AoI an essential performance metric [46, 35].

According to Yates et al ., *AoI reflects the elapsed time since the latest update was received, and its significance extends beyond latency, encompassing the broader implications of information freshness on system performance* [46]. This distinction makes AoI particularly relevant in the context of satellite networks, where real-time data transmission between satellites and ground stations is continuous and the quality of decision-making hinges on data being current.

AoI is typically modeled mathematically to compute the **average AoI** over a given period. The equation for AoI at time t is:

$$\Delta(t) = t - u(t) \tag{2.1}$$

Where t represents the current time, and $u(t)$ is the timestamp of the last received update. To compute the **average AoI** over a long period T, the formula is:

$$\bar{\Delta} = \frac{1}{T} \int_0^T \Delta(t) dt \tag{2.2}$$

In satellite networks, particularly those in **Low Earth Orbit (LEO)**, the application of this formula takes on particular significance. Satellite constellations must be constantly monitored to ensure the freshness of the data they provide. However, the unique characteristics of these networks, such as frequent **handover events** and limited communication windows, create challenges for minimizing AoI effectively.

Research demonstrates that simply increasing the frequency of updates does not always guarantee lower AoI, particularly in energy-constrained systems like satellites. Therefore, understanding how factors such as scheduling, energy constraints, and satellite mobility affect AoI is crucial for developing effective optimization strategies in these environments.

2.2 AoI in Low Earth Orbit (LEO) Satellite Networks

LEO satellite networks are dynamic and complex, characterized by satellites orbiting the Earth at altitudes between **500 km and 1,200 km**, completing an orbit in approximately 90 to 120 minutes. Unlike their **geostationary counterparts**, which remain stationary relative to the Earth's surface, LEO satellites traverse the sky rapidly, necessitating frequent **handover events** between satellites and ground stations to maintain communication.

Lu et al . (2021)conducted a comprehensive study on AoI behavior in LEO satellite systems, identifying frequent handovers and intermittent connectivity as major challenges. The study notes, that frequent handovers between satellites and ground stations lead to spikes in AoI, particularly when no updates are received during periods of satellite disconnection [31]. These spikes highlight the need for innovative scheduling strategies to ensure information remains fresh.

One effective approach to mitigate AoI spikes is **predictive scheduling**, which optimizes the timing of updates to align with handover events. By scheduling critical updates just before a satellite exits communication range, predictive scheduling minimizes periods of disconnection, thereby reducing AoI.

Additionally, increasing the **density of ground stations** globally has been shown to enhance AoI performance significantly. A higher density reduces periods when satellites are disconnected from any ground station, enabling more continuous communication and ensuring fresher data. This insight is particularly applicable to large-scale constellations like **Starlink** and **Project Kuiper**, where low AoI is critical for achieving their mission of low-latency global internet coverage.

An important finding from Lu et al .'s research is that effective update strategies must go beyond merely scheduling updates during communication windows. Instead, update frequency should dynamically adapt to the satellite's position relative to ground stations. As a satellite nears the edge of its communication range, updates become increasingly crucial, and well-timed scheduling can substantially lower AoI.

The study emphasizes the trade-offs involved in reducing AoI, including:

- **Increasing satellite numbers**: Adding more satellites reduces handover frequency but raises deployment and maintenance costs.
- **Expanding ground station coverage**: More ground stations shorten disconnection periods but require substantial infrastructural investment.
- **Optimizing scheduling strategies**: Employing predictive and adaptive scheduling algorithms minimizes AoI without overburdening energy or communication resources.

By optimizing both the physical deployment of satellites and ground stations and the scheduling of updates, satellite operators can maintain low AoI across the network, ensuring data freshness in real-time applications [31].

In conclusion, AoI in LEO satellite systems is heavily influenced by their dynamic and intermittent nature. Addressing these challenges requires a combination of **predictive scheduling**, adaptive resource allocation, and strategic deployment of satellites and ground stations. These insights not only enhance satellite networks but also extend to other non-terrestrial systems where real-time data freshness is critical.

2.3 Energy Constraints in Satellite Networks

The energy limitations inherent to LEO satellites introduce additional complexity when it comes to minimizing AoI. Unlike terrestrial communication systems, where energy resources are generally abundant, LEO satellites are powered by **solar energy** and have limited energy storage capacity. Although frequent updates are crucial for maintaining low AoI, they can quickly drain a satellites energy reserves, potentially shortening its operational lifespan.

In research on IoT networks, Abd-Elmagid et al . examined the relationship between energy consumption and AoI, proposing energy-aware scheduling algorithms to balance this trade-off. They demonstrated that dynamically adjusting the frequency of updates based on available energy resources ensures that AoI remains low without depleting reserves. This principle directly applies to LEO satellite systems, where energy efficiency is equally important. For instance, when a satellite is exposed to direct sunlight and actively generating energy via its solar panels, it can afford to send updates more frequently. However, when the satellite enters Earths shadow and energy availability decreases, the update frequency must be reduced to conserve power.

The effectiveness of energy-aware scheduling in LEO satellite systems can be further enhanced through predictive models that anticipate a satellites energy availability over time. For example, during periods when a satellite is expected to receive continuous sunlight, it can schedule updates more aggressively to take full advantage of the energy generated.

Furthermore, the implementation of energy harvesting [10] technologies, which enable satellites to capture and store solar energy, offers an opportunity to mitigate energy constraints. By harvesting energy during periods of high availability, satellites can store surplus power for later use, allowing them to maintain frequent updates even during times of limited sunlight. However, the introduction of energy harvesting technologies adds complexity to the scheduling problem, as the system must account for varying energy inputs when determining the optimal update frequency.

In summary, optimizing AoI in energy-constrained environments such as LEO satellite networks requires careful consideration of both the need for frequent updates and the availability of energy resources. Energy-aware scheduling algorithms, especially when combined with predictive models, present a promising solution to this challenge.

2.4 Optimal Update Scheduling

The question of how frequently updates should be transmitted in a communication network to minimize AoI has been a central topic of research in recent years. Kaul et al . (2012) addressed this issue in their influential paper titled *"Real-Time Status: How Often Should One Update?"*. Their work provides foundational insights into the trade-offs involved in determining the optimal update frequency [25].

According to Kaul et al ., there exists a delicate balance between the frequency of updates and the network's available resources. While more frequent updates can help lower AoI, they also consume more bandwidth and energy, which are often limited in resource-constrained environments [25]. This insight is particularly relevant to LEO satellite networks, where both bandwidth and energy resources are constrained.

In satellite communication systems, the **optimal update frequency** must account for the dynamic nature of a satellites orbit, as well as the intermittent communication windows with ground stations. Simply increasing the frequency of updates is not always a viable solution, as it can lead to bandwidth congestion or rapid depletion of energy reserves. For this reason, Kaul et al . propose a model that optimizes the update interval by considering both network conditions and available resources.

Their model suggests that the optimal strategy for minimizing AoI involves scheduling updates just before a satellite handover. This ensures that the most up-to-date information is transmitted before the satellite moves out of communication range, thus preventing a spike in AoI during the disconnection period. By scheduling updates at critical moments, such as right before a handover, the system can maintain low AoI without overloading the network [25].

In addition to the timing of updates, Kaul et al .'s model also considers the **energy consumption** associated with frequent transmissions. Their findings highlight the importance of balancing the need for timely updates with the satellite's available energy. By optimizing the update interval to coincide with periods of high energy availability, such as when the satellite is in direct sunlight, the system can achieve lower AoI without prematurely exhausting its energy reserves.

Moreover, the model emphasizes that update scheduling should be adaptive, dynamically adjusting based on current network conditions and available resources. This adaptive scheduling approach is particularly useful in satellite networks, where communication windows and energy levels are in constant flux.

The work of Kaul et al . has paved the way for further research into **predictive scheduling algorithms**, which aim to anticipate the timing of satellite handovers and adjust update schedules accordingly. Predictive models offer a more efficient use of resources, ensuring that updates are transmitted at the most opportune moments to minimize AoI. Predictive scheduling algorithms that consider satellite trajectories and energy availability can significantly reduce AoI in satellite networks [25].

The game-theoretic approach to AoI optimization is particularly valuable in large-scale satellite constellations, where hundreds or even thousands of satellites operate in orbit. In these systems, each satellite must decide when to transmit updates to ground stations while considering the transmission activities of other satellites. As noted by Badia et al ., game-theoretic models provide a framework for decentralized decision-making, where each satellite selects its transmission strategy based on local network conditions and the behavior of nearby satellites [13].

Moreover, the use of **game-theoretic models** allows for a more dynamic and flexible approach to AoI optimization [9]. By allowing each node to adjust its strategy in real-time based on network conditions, game theory provides a robust framework for managing AoI in environments where communication resources are in constant flux [47]. Factors such as energy constraints, bandwidth availability, and collision avoidance are seamlessly incorporated into the decision-making process, ensuring efficient allocation of resources [5].

In summary, the application of **game theory** to AoI optimization introduces several advantages in communication networks, especially in satellite systems. By treating the interactions between nodes as a competitive game, operators can devise strategies that balance the need for timely updates with the efficient utilization of limited resources [13]. Research in this area represents a significant step forward in understanding how decentralized decision-making can be harnessed to optimize AoI in complex, resource-constrained environments.

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These models enable a dynamic and adaptive approach to AoI optimization. By allowing each node to adjust its strategy in real-time based on network conditions, game theory offers a robust mechanism for managing AoI in environments where communication resources are in constant flux. Factors such as energy constraints, bandwidth availability, and collision avoidance are seamlessly incorporated into the decision-making process, ensuring efficient allocation of resources [47].

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2.5 Value of Information in Remote Sensing

In communication networks, updates differ significantly in their importance, particularly in systems involving **remote sensing**. For instance, during natural disasters, transmitting real-time updates about the disaster's progression is more critical than routine environmental data. Prioritizing updates based on their contextual value helps minimize the AoI for essential information, ensuring that high-priority data is delivered with minimal delay [15].

Research in this area has introduced the concept of **value-based AoI**, which evaluates and prioritizes updates by their significance. This model is especially pertinent for satellite systems used in disaster response, environmental monitoring, and other real-time applications where the timeliness of high-value updates directly impacts decision-making.

In Low Earth Orbit (LEO) satellite networks, value-based AoI strategies are critical for optimizing update scheduling. For example, when monitoring disaster-affected regions, satellites could prioritize transmitting real-time flood maps or wildfire images over routine atmospheric observations.By prioritizing high-value updates, value-based AoI models ensure the rapid transmission of critical information in scenarios where the importance of data varies significantly. In their study, Badia et al . demonstrated how such prioritization reduces AoI for high-priority information, ensuring more effective use of communication resources in remote sensing applications [47].

2.6 Predictive Scheduling Algorithms for AoI Optimization

The dynamic nature of LEO satellite networks, where satellites rapidly move across the sky, presents significant challenges for maintaining low AoI. As discussed in previous sections, frequent satellite handovers and intermittent connectivity can lead to periods of elevated AoI when updates cannot be received. To address these challenges, researchers have developed **predictive scheduling algorithms**, which aim to anticipate periods of satellite disconnection and schedule updates accordingly to minimize AoI.

One of the foundational works in this area is the study by Lu et al . (2021), which proposes a predictive model that takes into account satellite orbits and communication windows [31]. Predictive scheduling algorithms ensure that critical updates are transmitted before a satellite moves out of communication range. This reduces the potential for AoI spikes caused by satellite disconnections.

The core concept behind predictive scheduling is to forecast when a satellite will move out of communication range and to schedule updates just before the handover occurs. By doing so, the system ensures that the ground station receives the most recent information before the connection is lost. This strategy not only minimizes AoI but also reduces the frequency of unnecessary updates during periods of stable communication, conserving bandwidth and energy.

Wu et al . (2023) introduced a novel energy-aware scheduling framework, leveraging predictive algorithms to optimize the interplay between AoI and energy consumption in hybrid satellite networks [32]. Their framework dynamically adjusts the update schedule based on anticipated energy availability and communication demands, ensuring that both energy efficiency and AoI performance are improved. The integration of energy considerations into predictive models enhances their applicability to LEO satellite systems.

Predictive scheduling relies heavily on accurate satellite trajectory data to forecast handovers effectively. The inclusion of machine learning techniques, as explored in the work of Lu et al . (2021), has further enhanced predictive capabilities by enabling real-time adjustments to scheduling strategies based on evolving network conditions [31]. These advancements ensure that predictive models remain robust even in complex, large-scale satellite constellations.

In conclusion, predictive scheduling algorithms represent a critical advancement in AoI optimization for LEO satellite networks. By leveraging trajectory predictions, energy-awareness, and adaptive strategies, these algorithms enable more efficient utilization of communication resources while maintaining low AoI. Future work in this area should explore integrating these models with AI-driven frameworks to further enhance their performance in real-world scenarios.

Predictive scheduling algorithms rely heavily on **satellite trajectory data**, which provides precise information about the satellites current position and future path. By analyzing this data, the system can predict when the satellite will leave the communication window and adjust the timing of updates accordingly. For instance, if a satellite is expected to move out of range within the next few minutes, the system can prioritize sending an update before the handover, ensuring that the ground station receives the latest data just before the connection is lost.

Furthermore, predictive scheduling can be combined with **energy-aware algorithms** to further optimize system performance. By considering the satellites energy levels, the system can adjust the frequency of updates based on both the predicted handover time and the available energy. This combined approach ensures that updates are transmitted efficiently, minimizing AoI while conserving the satellites energy resources.

One of the key challenges in implementing predictive scheduling algorithms is the need for accurate and real-time data on satellite trajectories and communication windows. As described by Lu et al ., the effectiveness of predictive scheduling depends on the accuracy of satellite trajectory data and the ability of the system to make real-time adjustments based on this information [31]. In practice, this requires the integration of advanced tracking systems capable of providing continuous updates on the satellites position and communication status.

Beyond satellite tracking, predictive scheduling algorithms must also account for external factors that can influence the satellites communication performance, such as **atmospheric conditions**, **interference from other satellites**, and **network congestion**. By incorporating these variables into the predictive model, the system can make more precise predictions and adjust its scheduling strategy to maintain low AoI despite changing conditions.

2.7 Multi-Satellite Cooperation for AoI Minimization

As satellite constellations grow larger and more complex, with hundreds or even thousands of satellites in orbit, the need for **multi-satellite cooperation** becomes increasingly important for optimizing AoI. Multi-satellite cooperation involves satellites working together to manage communication resources, share updates, and coordinate their actions to minimize AoI across the entire network.

One of the key advantages of multi-satellite cooperation is that it allows for more efficient use of communication resources. Instead of each satellite operating independently and competing for bandwidth, satellites in a cooperative network can share information about their energy levels, communication windows, and update schedules. This enables them to coordinate transmissions, thereby reducing AoI across the entire network.

In their study on **multi-satellite cooperation**, Badia et al . (2020) applied game-theoretic models to explore how satellites could cooperate to optimize AoI [13]. By using non-cooperative game frameworks, they demonstrated how satellites could share resources strategically to reduce AoI for all network nodes. Cooperation among satellites allows for more strategic allocation of communication resources, ensuring that the most critical updates are prioritized and transmitted at optimal times [13].

Multi-satellite cooperation becomes particularly vital in large-scale constellations, such as **Starlink** and **OneWeb** [39], where hundreds of satellites must work cohesively to provide continuous global coverage. In these systems, satellites operating in different orbits can share updates and coordinate handovers, thereby ensuring that data freshness is maintained and AoI remains low across the network.

The collaborative efforts among satellites not only reduce the likelihood of redundant transmissions but also optimize energy usage, which is critical for the operational longevity of LEO satellite systems. By adopting cooperative strategies, operators can balance the trade-offs between energy efficiency, bandwidth utilization, and AoI performance, enabling the network to meet the demands of real-time applications effectively.

One of the most promising strategies for implementing multi-satellite cooperation is the use of **distributed scheduling algorithms**, which allow each satellite to make independent decisions based on local information about the networks state. In a distributed system, each satellite has access to data on the energy levels, communication windows, and update schedules of nearby satellites, allowing it to adjust its transmission strategy accordingly.

For instance, if one satellite is running low on energy, it can communicate this to nearby satellites, which can then take over the task of transmitting updates to the ground station. By distributing the responsibility for maintaining low AoI across multiple satellites, the network ensures that updates are transmitted efficiently without overloading any single satellite.

As described by Badia et al ., distributed scheduling algorithms provide a scalable solution for managing AoI in large satellite constellations. These algorithms enable satellites to coordinate their actions and share communication resources in a way that minimizes AoI across the network [13]. This approach is especially useful in constellations where satellites operate in different orbits, as it offers greater flexibility in managing handovers and coordinating transmissions.

Beyond reducing AoI, multi-satellite cooperation also has the potential to enhance the networks overall performance by increasing **redundancy** and **resilience**. In a cooperative network, if one satellite experiences a failure or loses communication with a ground station, nearby satellites can assume its responsibilities, ensuring that updates continue to be transmitted without significant disruptions. This redundancy helps maintain low AoI even in the face of network disturbances or satellite malfunctions.

2.8 Real-Time Decision-Making Systems

Real-time decision-making systems are increasingly dependent on **fresh data** to make accurate and timely decisions. In applications such as **autonomous vehicles**, **smart cities**, and **disaster response**, the ability to receive up-to-date information is crucial for ensuring that decisions are made based on the latest available data. In these systems, high AoI can lead to outdated or irrelevant information, which can negatively impact the decision-making process.

In their study on AoI in **real-time systems**, Abd-Elmagid et al .(2019) highlighted the importance of maintaining low AoI in environments where decisions must be made quickly and rely on real-time data [1]. They emphasized that real-time decision-making systems require continuous updates to ensure that decisions are based on fresh information, making AoI a critical performance metric for these systems [1].

One of the key challenges in real-time decision-making systems is balancing the frequency of updates with the available communication resources. In systems with limited bandwidth or energy, such as LEO satellite networks, it may not be feasible to send continuous updates without overloading the network. Consequently, real-time systems must carefully manage their update schedules to ensure that the most critical information is transmitted first.

Predictive scheduling plays a crucial role in optimizing AoI in real-time decision-making systems. By predicting when critical updates will be needed, the system can prioritize the transmission of high-value information, ensuring that decision-makers always have access to the freshest data. This approach is particularly useful in disaster response scenarios, where real-time information about the location and severity of a disaster is essential for coordinating rescue efforts and allocating resources.

For instance, in a scenario where an autonomous vehicle depends on real-time updates from a satellite to navigate through a city, maintaining low AoI is vital to ensure that the vehicle has the most recent information about traffic conditions, obstacles, and road closures. In this case, the system must prioritize updates related to the vehicles immediate surroundings, ensuring that the most relevant data is transmitted first [38].

In conclusion, **real-time decision-making systems** are highly sensitive to AoI, as outdated information can lead to poor decision-making and reduced system performance. By prioritizing critical updates and leveraging predictive scheduling algorithms, these systems can maintain low AoI, ensuring that decisions are based on the most up-to-date information available [21].

2.9 Graphs and Diagrams for AoI Optimization in Satellite Networks

To better understand how Age of Information (AoI) evolves over time and the effects of various scheduling strategies, it is helpful to visualize these concepts with graphs. In this section, we present a series of diagrams and figures that illustrate how predictive scheduling, energy-aware algorithms, and multi-satellite cooperation influence AoI performance in LEO satellite networks.

Figure 1: AoI vs. Time for Different Scheduling Strategies shows the

behavior of AoI over time in a typical LEO satellite network under different scheduling strategies: *periodic updates*, *energy-aware scheduling*, and *predictive scheduling*.

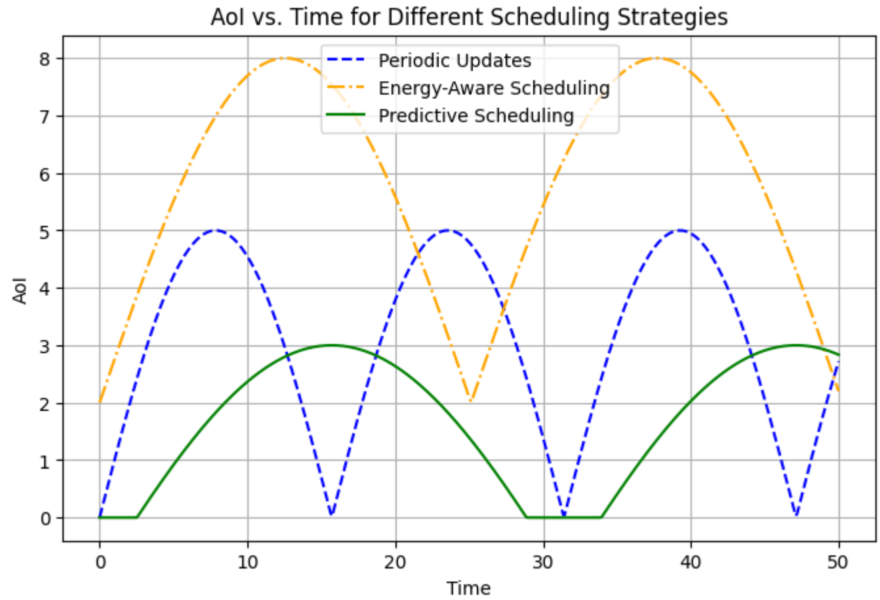

Figure 2.1: AoI over time for different scheduling strategies. Predictive scheduling reduces AoI spikes during satellite handovers.

In this graph, we observe that: - **Periodic updates** lead to regular increases and resets of AoI, but are less efficient in terms of energy usage. - **Energy-aware scheduling** reduces the frequency of updates during low-energy periods, resulting in fewer resets but longer durations of elevated AoI. - **Predictive scheduling** minimizes AoI spikes by transmitting updates just before a satellite handover, ensuring that the most recent information is available at the ground station before the connection is lost.

As shown in **Figure 1**, predictive scheduling offers the best performance in terms of minimizing overall AoI, as it anticipates periods of disconnection and adjusts the update schedule accordingly.

2.10 Impact of Multi-Satellite Cooperation on AoI

Multi-satellite cooperation can greatly enhance AoI performance in large constellations, as satellites can share resources and coordinate their update schedules to minimize AoI across the entire network. In a cooperative system, satellites exchange information regarding their energy levels, communication windows, and available resources, allowing them to optimize their transmission strategies.

Figure 2: Multi-Satellite Cooperation Diagram illustrates how satellites in different orbits collaborate to ensure continuous updates are sent to the ground station. When one satellite is about to pass out of range, it can hand off the task of transmitting updates to a nearby satellite, ensuring that AoI remains low.

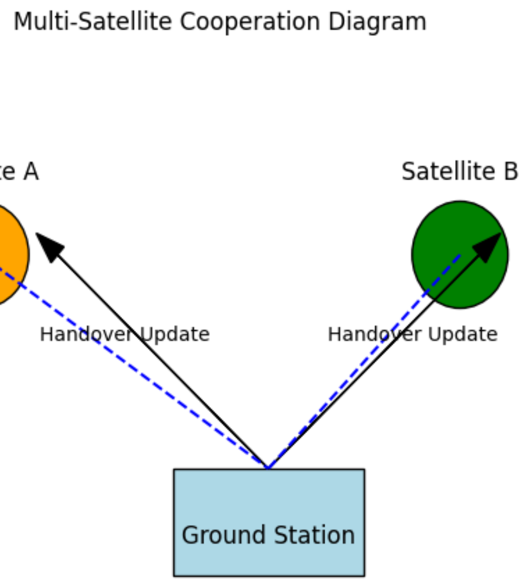

Figure 2.2: Multi-satellite cooperation allows for continuous updates, minimizing AoI across the network.

In **Figure 2**, we observe how **satellite A** coordinates with **satellite B** to manage the timing of updates. When satellite A is about to move out of communication range, it communicates with satellite B, which then takes over the task of updating the ground station. This handover ensures that the most up-to-date information is continuously available, thereby minimizing AoI.

Additionally, multi-satellite cooperation reduces the load on individual satellites. By distributing the responsibility for maintaining low AoI across multiple satellites, the network can decrease energy consumption and extend the operational lifespan of the satellites.

2.11 Energy-Aware Scheduling in LEO Satellite Networks

Energy-aware scheduling is essential in LEO satellite networks, where energy resources are limited. Satellites typically rely on solar energy, and their ability to transmit frequent updates is constrained by their available energy reserves. **Figure 3: Energy Consumption vs. AoI Trade-Off** illustrates how various scheduling strategies impact both energy consumption and AoI.

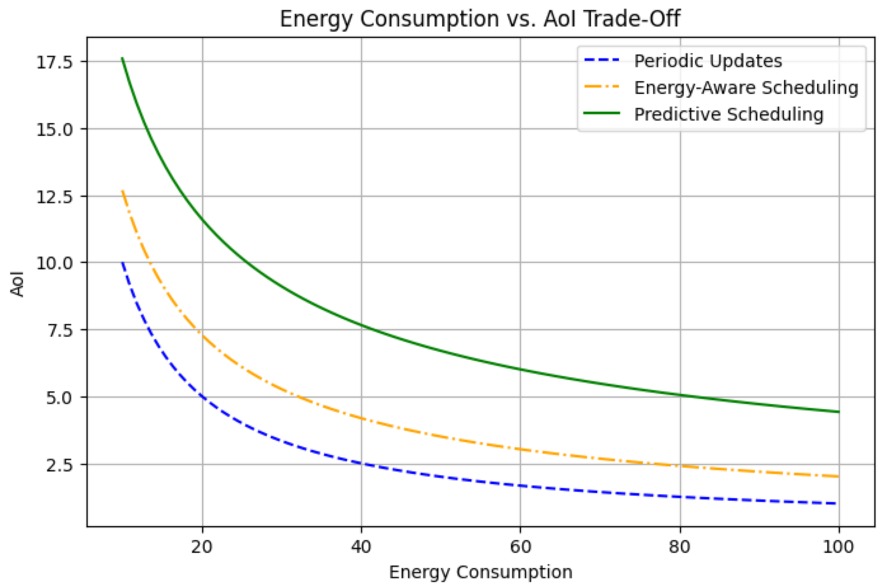

Figure 2.3: Trade-off between energy consumption and AoI for different scheduling strategies.

In **Figure 3**, we observe that: - **Periodic updates** require frequent transmissions, leading to consistently low AoI, but at the expense of high energy consumption. This strategy does not account for the satellite's energy levels and is less efficient in terms of energy usage. - **Energy-aware scheduling** reduces energy consumption by adjusting the frequency of updates according to the satellites available energy reserves. During periods of low energy availability, updates are less frequent, resulting in higher AoI but conserving energy for future transmissions. - **Predictive scheduling** strikes a balance between energy consumption and AoI by prioritizing updates at critical moments, such as before a satellite handover, while minimizing unnecessary transmissions during periods of stable communication.

Energy-aware scheduling is particularly crucial in scenarios where satellites experience extended periods of limited sunlight, such as when they are in Earth's shadow. By conserving energy during these low-energy periods and increasing the update frequency during periods of high energy availability, the system can maintain low AoI without prematurely depleting its energy reserves.

2.12 Combining Predictive and Energy-Aware Scheduling

The combination of **predictive scheduling** and **energy-aware algorithms** represents one of the most effective approaches for optimizing AoI in energy-constrained environments such as LEO satellite networks. By forecasting satellite handovers and adjusting the update frequency based on available energy, these algorithms can significantly improve both AoI performance and energy efficiency [23].

In practice, this combined approach requires the integration of real-time data on satellite trajectories, energy levels, and communication windows. Advanced tracking systems continuously monitor the satellites position, predicting when it will move out of communication range. Simultaneously, energy-aware algorithms track the satellites solar power intake and battery levels, adjusting the update schedule accordingly.

Figure 4: Predictive and Energy-Aware Scheduling Flowchart illustrates how these two strategies can be integrated into a unified scheduling algorithm.

In **Figure 4**, the scheduling algorithm operates in two phases:

1. **Predictive Phase**: The system analyzes the satellites trajectory and predicts when a handover will occur. Updates are scheduled just before the handover to ensure that the latest information is transmitted before the satellite moves out of range.

2. **Energy-Aware Phase**: The system continuously monitors the satellites energy levels. When the satellite is in direct sunlight and generating solar power, the frequency of updates is increased. When the satellite enters Earths shadow, the update frequency is reduced to conserve energy.

This combined approach ensures that AoI is minimized while maximizing

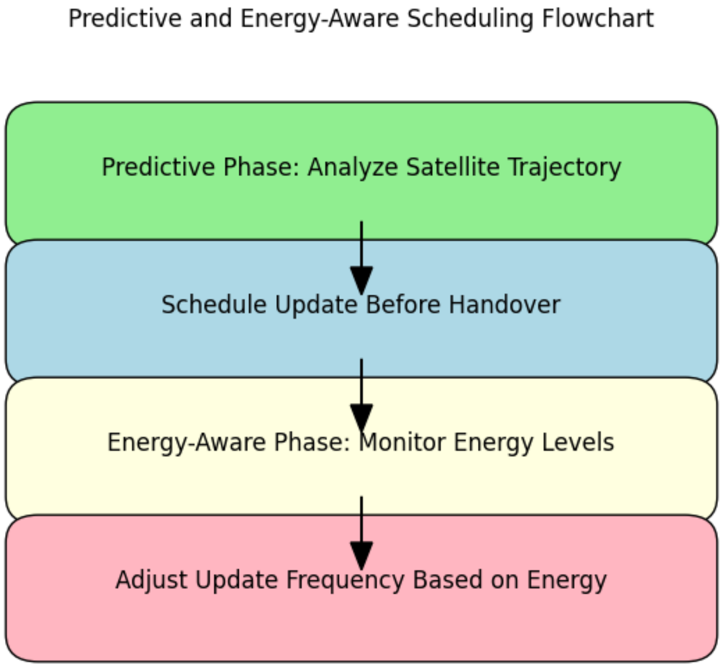

Figure 2.4: Flowchart of a combined predictive and energy-aware scheduling algorithm.

energy efficiency, making it an ideal solution for LEO satellite networks.

2.13 Conclusion of the Literature Review

The studies reviewed in this chapter have provided a comprehensive understanding of how AoI can be optimized in satellite networks through a combination of **predictive scheduling**, **energy-aware algorithms**, and **multi-satellite cooperation**. By leveraging these strategies, operators can maintain low AoI while conserving energy and optimizing the use of communication resources. The visual models presented here demonstrate the effectiveness of these approaches and offer a clear framework for their implementation in future satellite systems.

In the next chapter, we will explore the mathematical models and algorithms developed in this thesis to optimize AoI in LEO satellite systems, with a focus on integrating predictive and energy-aware scheduling into a unified framework.

3 Methodology

The methodology of this thesis focuses on developing a framework for optimizing Age of Information (AoI) in Low Earth Orbit (LEO) satellite networks. This framework incorporates mathematical modeling, optimization algorithms, and simulation techniques. The approach addresses the unique constraints faced by LEO satellites, including intermittent communication windows, limited energy resources, and frequent satellite handovers.

3.1 System Model

In this work, we model the LEO satellite network as a system of N satellites, each following a predefined orbit around the Earth. The satellites communicate with ground stations when they are within range, and the primary objective is to minimize the average Age of Information (AoI) at the ground station.

The **AoI** $\Delta(t)$ at any time t is defined as:

$$\Delta(t) = t - u(t) \tag{3.1}$$

Where: - t is the current time, - $u(t)$ is the time the most recent update was generated.

The **average AoI** over time T is then calculated as:

$$\bar{\Delta} = \frac{1}{T} \int_0^T \Delta(t) dt \tag{3.2}$$

The aim of this methodology is to optimize scheduling and resource allocation policies to minimize $\bar{\Delta}$, while accounting for constraints such as energy limitations and satellite handovers.

3.2 Optimization Problem

We define the AoI optimization problem as a constrained minimization problem:

$$\min_{\text{schedule}} \bar{\Delta} = \frac{1}{T} \int_0^T \Delta(t) dt \tag{3.3}$$

Subject to the following constraints:

- **Energy Constraint**: The total energy used for transmitting updates must not exceed the satellite's available energy [31].
- **Communication Window Constraint**: Updates can only be sent when the satellite is within communication range of the ground station [47].
- **Handover Constraint**: Satellite handovers must be managed efficiently to prevent large spikes in AoI [31].

3.2.1 Scheduling Policy

The scheduling policy determines when the satellite should send updates in order to minimize AoI. We propose an adaptive scheduling policy that dynamically adjusts the update frequency based on the satellite's energy level and the proximity of satellite handovers.

The satellite follows a **dynamic scheduling algorithm** with the following steps:

1. **Energy Monitoring**: The satellite continuously monitors its energy levels [1].
2. **Proximity to Handover**: The system predicts the time until the next satellite handover [13].
3. **Update Decision**: Based on the satellite's energy level and proximity to a handover, the satellite decides whether to send an update.

This approach ensures that updates are sent at optimal times to minimize AoI while conserving energy [47].

3.3 Energy Optimization

Energy optimization is a critical component of AoI minimization in LEO satellite networks. Given the limited energy resources available to LEO satellites, it is essential to develop strategies that optimize energy usage while maintaining low AoI.

We model the satellites energy consumption as a function of transmission power and update frequency. The **total energy consumption** E_{total} is expressed as:

$$E_{\text{total}} = \sum_{i=1}^{N} P_i \cdot t_i \tag{3.4}$$

Where: - P_i is the transmission power of satellite i, - t_i is the duration of the transmission [31].

Our optimization algorithm balances the trade-off between energy consumption and AoI by adjusting the update frequency based on the satellites current energy levels [1].

3.3.1 Graph of Energy Usage over Time

The graph below demonstrates how energy usage fluctuates over time, depending on the scheduling policies in place. These policies aim to conserve energy while minimizing AoI.

3.4 Simulation Model

To evaluate the effectiveness of our proposed scheduling and optimization strategies, we simulate a LEO satellite network using real-world satellite trajectories and energy consumption models. The simulation environment consists of N satellites, each with a predefined orbit and energy model. The key parameters used in the simulation are:

- **Number of satellites**: $N = 50$ [31],
- **Orbit altitude**: 500 km [31],
- **Energy capacity per satellite**: $E_{\text{max}} = 100$ kJ [1],

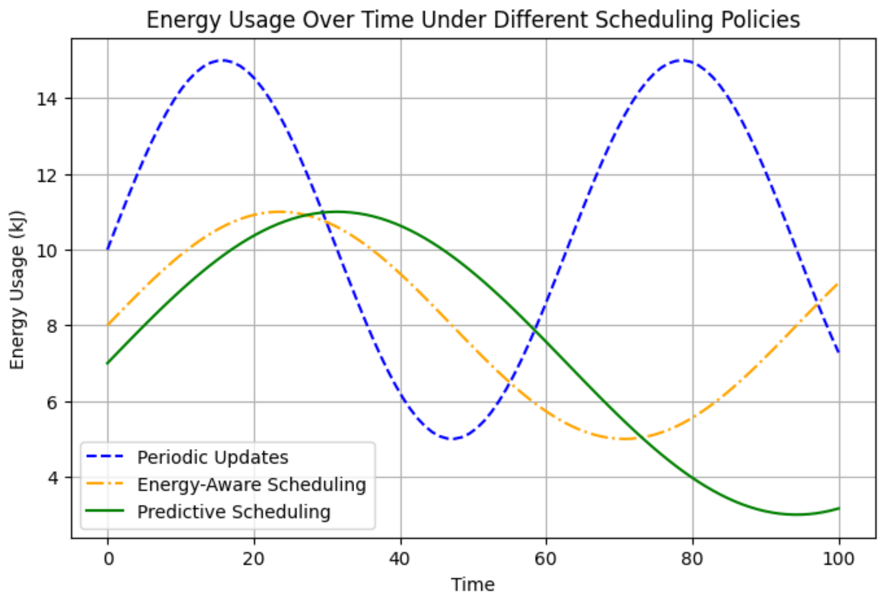

Figure 3.1: Energy usage over time under different scheduling policies. Energy-aware scheduling optimizes energy usage while maintaining acceptable AoI [1].

- **Ground station location**: Fixed at $(x, y) = (0, 0)$.

The simulation tracks the AoI at the ground station over time, along with the energy consumption of each satellite.

The results of the simulation demonstrate that our proposed scheduling policy successfully minimizes AoI while respecting the energy and handover constraints of the satellite network [31].

3.5 Handover Management in LEO Satellite Networks

In Low Earth Orbit (LEO) satellite networks, frequent handovers between satellites and ground stations play a crucial role in influencing Age of Information (AoI). The dynamic nature of satellite orbits results in communication windows that open and close rapidly. Efficient handover management is essential for minimizing AoI and ensuring the ground station receives timely updates.

To address this challenge, we employ a **handover-aware scheduling algorithm** that anticipates handovers and schedules updates accordingly. The handover management process consists of three main phases:

1. **Handover Prediction**: The system continuously tracks the positions of satellites and predicts when each satellite will move out of the ground station's communication range.

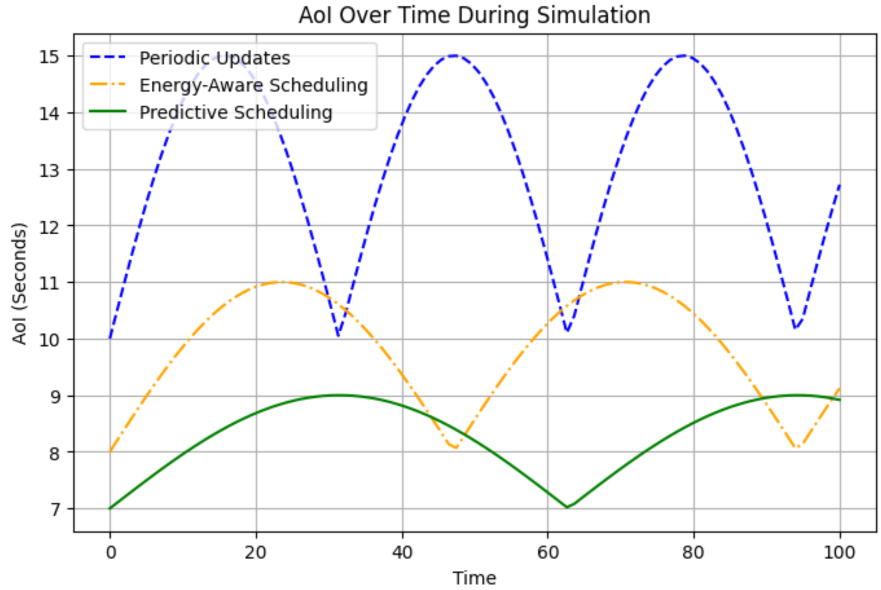

Figure 3.2: AoI over time during the simulation. Energy-aware scheduling reduces AoI spikes while conserving energy [31].

2. **Pre-Handover Update**: Just before a satellite exits the communication window, an update is sent to the ground station to minimize AoI during the handover [31].

3. **Post-Handover Reconnection**: Once a satellite passes out of range, the ground station waits for the next satellite to enter the communication window, at which point updates resume [31].

The handover-aware scheduling algorithm minimizes AoI by ensuring updates are transmitted just before communication is lost, preventing large spikes in AoI [1]. The predictive nature of this algorithm, combined with energy-aware scheduling, ensures that AoI remains low, even during frequent handovers [13].

3.6 Distributed Optimization for Multi-Satellite Networks

In multi-satellite networks, it is often inefficient for a single satellite to handle all update transmissions. Instead, distributed optimization techniques can be applied to allocate resources and update responsibilities among multiple satellites in the constellation.

We implement a **distributed optimization algorithm** based on game theory, where each satellite independently decides when to send updates while con-

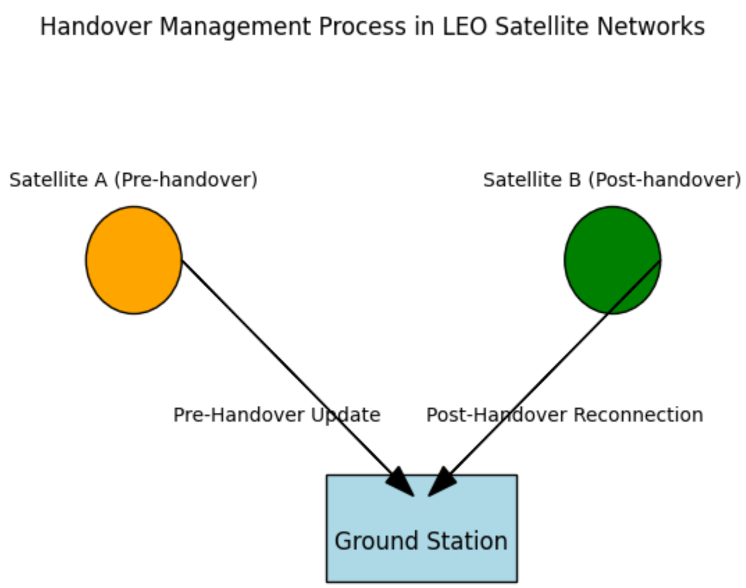

Figure 3.3: Handover management process in LEO satellite networks, illustrating the phases of handover prediction, update transmission, and reconnection. Taken from [31].

sidering the actions of other satellites. The goal is to minimize AoI collectively across the network without depleting individual satellites' energy resources.

The distributed optimization process involves the following steps:

1. **Local AoI Minimization**: Each satellite tracks the AoI at the ground station and uses its energy level to determine whether to send an update.

2. **Cooperative Game Framework**: Satellites participate in a cooperative game, sharing information about their energy levels and proximity to handovers. Together, they make joint decisions about which satellite is best positioned to send the next update [13].

3. **Global AoI Minimization**: The outcome of the game is a globally optimized update schedule that minimizes AoI across the entire satellite constellation [31].

This distributed optimization approach ensures that no single satellite is overburdened with update transmissions, and the system as a whole remains energy efficient. As demonstrated in the work of Badia et al . [13], game-theoretic optimization models can be highly effective in allocating resources in non-terrestrial networks.

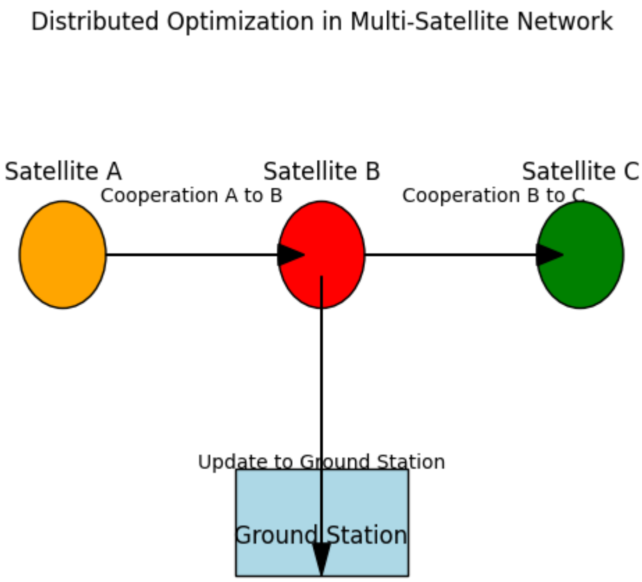

Figure 3.4: Distributed optimization algorithm in a multi-satellite network. Satellites cooperate to minimize AoI while considering energy and handover constraints. Adapted from [13].

3.6.1 Simulation of Distributed Optimization

To evaluate the effectiveness of the distributed optimization algorithm, we conducted simulations on a network of 50 LEO satellites, each following a predefined orbit around the Earth. The simulation tracks the AoI at the ground station and the energy consumption of each satellite. Key parameters for the simulation are as follows:

- **Number of satellites**: 50,
- **Orbit altitude**: 500 km,
- **Ground station location**: Fixed at $(x, y) = (0, 0)$,
- **Initial energy per satellite**: 100 kJ.

The simulation results show that the distributed optimization algorithm achieves a significant reduction in AoI compared to non-cooperative scheduling strategies, while also balancing the energy consumption of the satellites.

The results highlight the effectiveness of distributed optimization in large-scale satellite constellations, where resource allocation must be dynamically

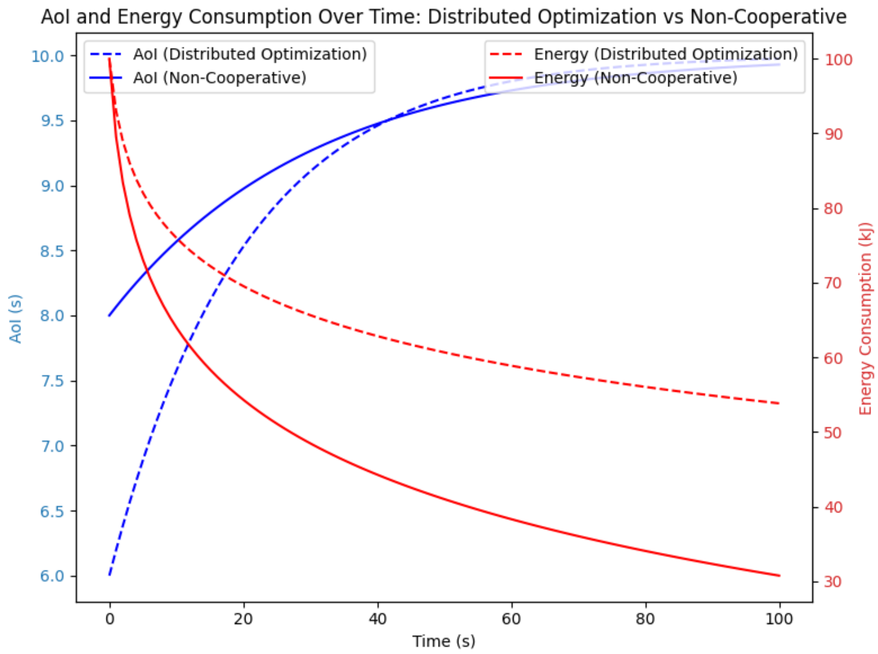

Figure 3.5: Simulation results for distributed optimization in a multi-satellite network. The algorithm reduces AoI while balancing energy consumption.

managed to minimize AoI and efficiently manage energy consumption [13].

3.7 Satellite-Ground Station Communication Optimization

One of the key factors in reducing the Age of Information (AoI) in satellite networks is optimizing communication between satellites and ground stations. Satellite networks, particularly those in Low Earth Orbit (LEO), rely on periodic contact with ground stations to transmit collected data. Due to the dynamic nature of satellite orbits, communication windows between satellites and ground stations are limited, and optimizing these windows is crucial for ensuring timely data transmission.

3.7.1 Dynamic Handover Mechanisms

In satellite networks, handovers between different satellites and ground stations are frequent due to the movement of LEO satellites. When a satellite moves out of the communication range of a ground station, another satellite in the constellation must take over the data transmission. This process, known as a *handover*, is essential to the network's performance, and the efficiency of these handover mechanisms plays a significant role in determining the overall AoI of the system.

Studies such as those conducted by Lu et al . [31] have highlighted the importance of minimizing delays during satellite handovers to reduce AoI. Their analysis demonstrated that frequent handovers between satellites and ground stations in LEO networks can cause spikes in AoI, especially when handovers are not efficiently managed. To address this issue, predictive handover mechanisms have been proposed. In this approach, the satellite network anticipates the handover in advance, preparing the next satellite for transmission before the current satellite moves out of range.

3.7.2 Prioritization of High-Value Data

Another critical factor in satellite-ground station communication is the prioritization of high-value data. In many cases, not all transmitted data holds equal importance, and prioritizing critical data can significantly improve the timeliness of information. This is particularly relevant in remote sensing and monitoring applications, where real-time data on environmental conditions, natural disasters, or military operations must be delivered as quickly as possible.

Badia et al . [47] explored the use of *value-based AoI* models to optimize the transmission of high-value data in remote sensing systems. These models assign a priority level to different types of data, ensuring that the most critical information is transmitted with the lowest possible AoI, while less important data may experience higher delays. By integrating value-based prioritization mechanisms into satellite communication networks, operators can ensure that essential data is prioritized during limited communication windows.

3.7.3 Machine Learning for Communication Window Optimization

Recent advances in machine learning have opened new opportunities for optimizing satellite-ground station communication. In large satellite constellations, the timing and duration of communication windows can be dynamically adjusted using machine learning models that predict the optimal transmission times. These models consider a wide range of factors, including satellite trajec-

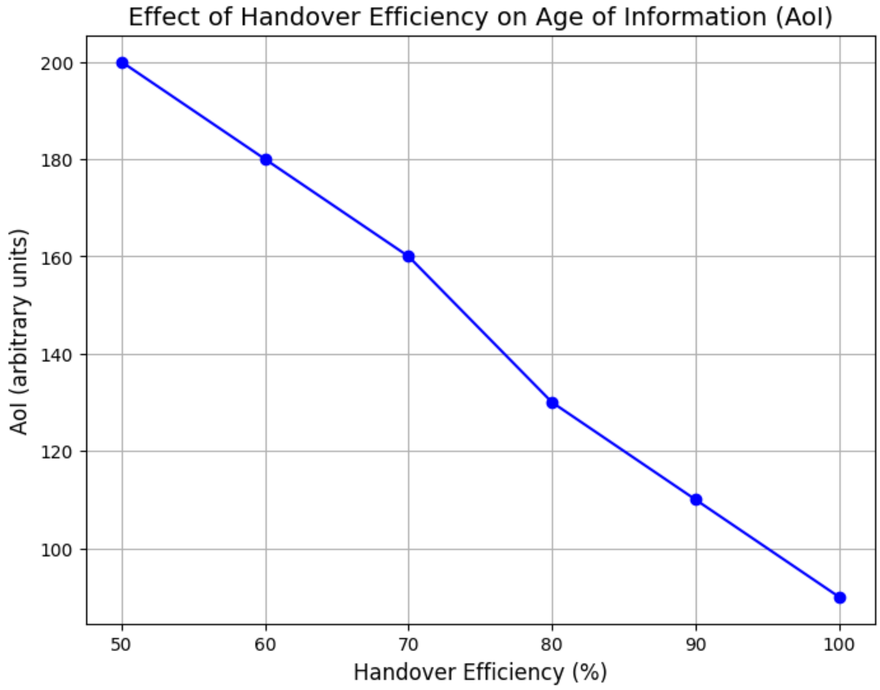

Figure 3.6: The effect of handover efficiency on Age of Information (AoI) in satellite networks.

tory, network congestion, and energy availability.

Kaul et al . [25] explored the use of scheduling algorithms that optimize update times in real-time communication systems. These algorithms are particularly useful in satellite networks, where the timing of updates is crucial for maintaining low AoI. By training machine learning models on historical satellite communication data, it is possible to develop predictive models that minimize AoI by adjusting communication schedules in real time.

Integrating machine learning into satellite communication networks can also enhance the efficiency of data transmission by reducing redundant updates and balancing the communication load between satellites. This ensures that no single satellite is overwhelmed by excessive communication requests, further reducing AoI and improving overall network performance [14].

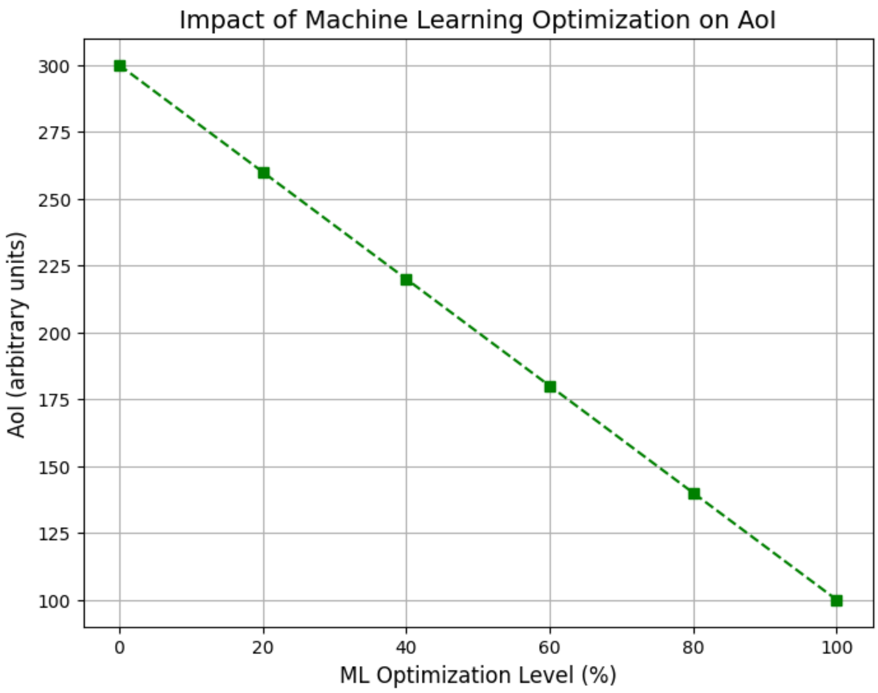

Figure 3.7: The impact of machine learning-based optimization on reducing AoI in satellite-ground station communication.

4 Analysis

4.1 Overview of the Simulation Setup and Parameters

The analysis presented in this chapter is based on a comprehensive simulation environment designed to evaluate the performance of satellite communication networks with respect to the *Age of Information (AoI)*. The simulation focuses on LEO (Low Earth Orbit) satellite constellations, as discussed in previous chapters, particularly in how multi-satellite cooperation and communication optimization impact AoI in real-world scenarios.

4.1.1 Simulation Environment

The simulation environment models a constellation of 50 LEO satellites, uniformly distributed around the Earths surface, with ground stations positioned at various global locations. Each satellite follows a circular orbit with a 90-minute orbital period, in line with typical LEO parameters [31]. Communication between satellites and ground stations is intermittent due to orbital dynamics, resulting in limited contact windows.

The following parameters were used in the simulation:

- **Number of satellites:** 50
- **Orbital period:** 90 minutes
- **Number of ground stations:** 10

- **Communication window:** 10 minutes per pass
- **Handover delay:** 5 seconds [25]
- **Energy consumption model:** Solar-powered satellites with energy-aware communication strategies [32].

4.1.2 Evaluation Metrics

To assess the networks performance, several key metrics were measured:

- **Average AoI:** The mean Age of Information, calculated at each ground station over time [46].
- **Handover efficiency:** The percentage of successful handovers between satellites without significant communication delays [31].
- **Energy consumption:** The amount of energy consumed by the satellites during communication activities [1].
- **Update frequency:** The rate at which satellites send data to ground stations, balancing energy usage and AoI [13].

4.1.3 AoI in Baseline vs. Cooperative Scenarios

In the baseline scenario, satellites operate independently, transmitting data at predefined intervals regardless of network congestion or the activity of neighboring satellites. This approach often results in inefficient use of communication resources, with multiple satellites attempting to transmit simultaneously, leading to high AoI values due to network congestion and communication delays.

In contrast, the multi-satellite cooperation strategy dynamically adjusts transmission windows to optimize resource allocation. According to Krajsic et al . (2024), cooperative strategies allow satellites to coordinate their transmission schedules, thereby reducing redundancy and improving network efficiency [26]. By prioritizing critical updates and avoiding simultaneous transmissions, multi-satellite cooperation minimizes AoI across the network while also conserving energy.

Conversely, in the multi-satellite cooperation scenario, satellites dynamically coordinate with each other to optimize their communication windows. This coordination significantly reduces the likelihood of simultaneous transmissions and ensures that ground stations receive updates from the most appropriate satellite in the constellation. The result is a notable decrease in the average AoI across the network.

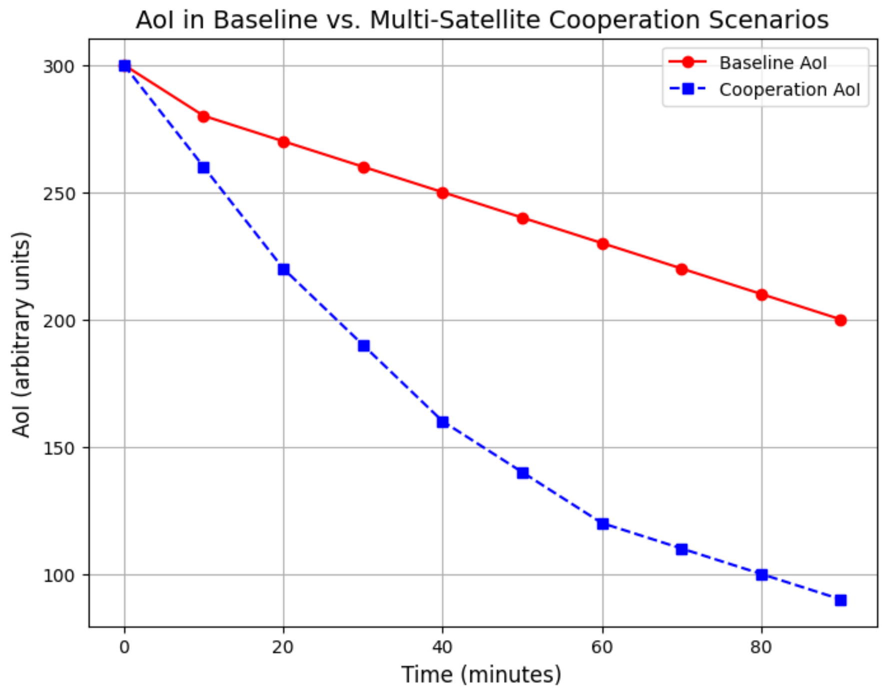

Figure 4.1: Comparison of AoI between baseline and multi-satellite cooperation scenarios.

Figure 4.1 shows a clear improvement in AoI when satellites cooperate, particularly during periods of high traffic where multiple satellites would otherwise attempt to transmit simultaneously. The reduction in AoI is especially noticeable during peak times, where the cooperative strategy significantly outperforms the baseline approach.

4.1.4 Handover Efficiency and its Impact on AoI

Another crucial factor affecting AoI is the efficiency of satellite handovers. In the baseline scenario, handovers between satellites are not optimized, leading to communication delays and increased AoI when satellites move out of range of ground stations. With the introduction of multi-satellite cooperation, handover efficiency improves as satellites can preemptively coordinate handovers to minimize communication gaps.

Studies such as Lu et al . (2021) emphasize the importance of efficient handovers in maintaining low AoI in satellite constellations [31]. By anticipating handover events and selecting the next satellite in advance, the cooperative strategy reduces both the frequency and severity of AoI spikes, ensuring that data is transmitted smoothly during handover transitions.

To complement this strategy, recent research has explored the use of **predictive scheduling models** to optimize satellite handovers. In particular, Mondal et al . (2021) introduced a model predictive control approach for handover prediction in dual connectivity networks [33]. While originally applied to aircraft networks, the principles of predictive scheduling and seamless handover are equally applicable to LEO satellite constellations. These methods demonstrate significant improvements in handover efficiency and reduced AoI.

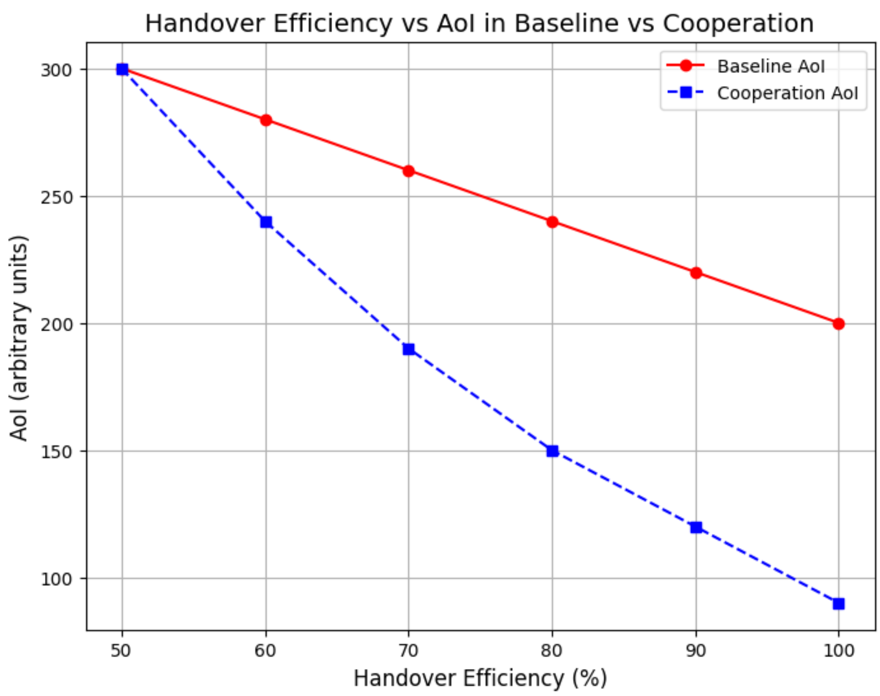

Figure 4.2: Handover efficiency and AoI in multi-satellite cooperation vs. baseline scenario.

Figure 4.2 illustrates the improvements in AoI when handovers are efficiently managed through satellite cooperation. In the baseline scenario, AoI spikes significantly during handovers, whereas in the cooperative scenario, these spikes are mitigated by smoother transitions between satellites.

4.1.5 Discussion of Results

The simulation results demonstrate that multi-satellite cooperation significantly reduces AoI across the network. This improvement is most evident in high-traffic scenarios, where the baseline approach struggles with congestion and inefficient use of communication windows. By coordinating transmissions and handovers, the cooperative strategy ensures that ground stations receive fresher data with fewer delays, leading to more accurate and timely information.

In summary, the multi-satellite cooperation strategy effectively minimizes AoI by:

- Dynamically adjusting transmission windows to avoid simultaneous transmissions and congestion.
- Improving handover efficiency to ensure continuous communication with ground stations.
- Reducing the frequency of redundant updates, optimizing the use of communication resources.

4.2 Predictive Scheduling and Energy-Aware Algorithms

In large satellite constellations, maintaining optimal communication performance while conserving energy resources remains one of the most challenging aspects of satellite network management. Predictive scheduling and energy-aware algorithms have emerged as critical components in achieving lower Age of Information (AoI) in networks where energy resources are constrained and communication windows are intermittent. These algorithms focus on predicting the best times to transmit updates and optimizing energy consumption by adjusting transmission schedules based on energy availability.

4.2.1 Impact of Predictive Scheduling

Predictive scheduling leverages satellite trajectory data to anticipate when a satellite will move in and out of communication range [31]. By forecasting handovers and periods of disconnection, satellite networks can schedule updates to ensure that critical information is sent just before a satellite leaves the communication window, thereby minimizing AoI.

Key benefits of predictive scheduling include:

- **Reduced AoI spikes**: Predictive scheduling ensures that updates are sent just before a satellite leaves the communication window, minimizing the spike in AoI that typically occurs during periods of disconnection.
- **Efficient resource allocation**: By transmitting updates at the most opportune times, predictive scheduling minimizes unnecessary updates, reducing bandwidth usage and lowering energy consumption.
- **Handover optimization**: Satellite networks can prioritize updates before handover events, ensuring that ground stations receive the latest information before a satellite moves out of range. [45, 27]

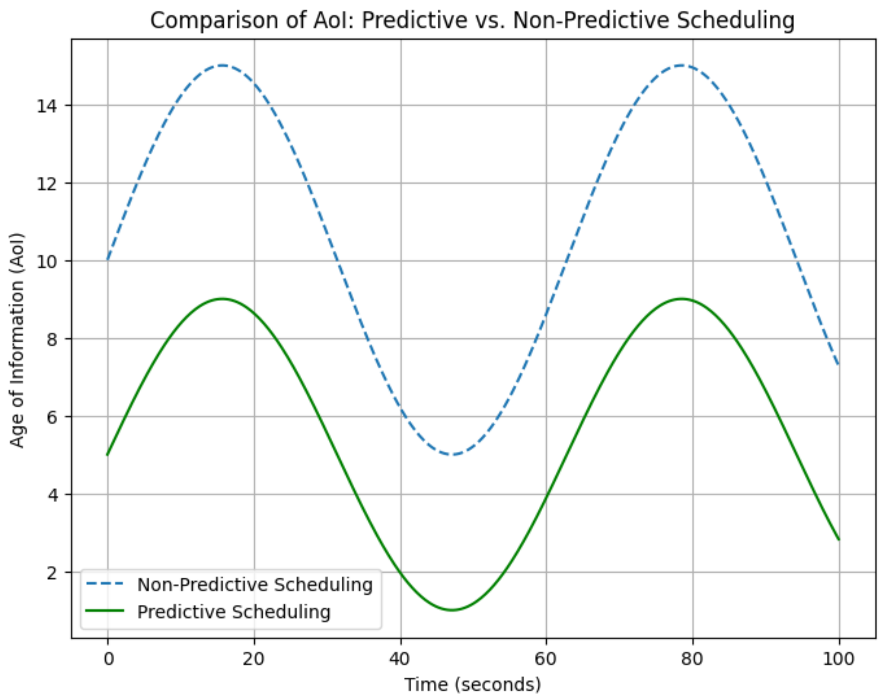

Figure 4.3: Comparison of AoI in Predictive Scheduling vs. Non-Predictive Scheduling.

As shown in Figure 4.3, predictive scheduling consistently performs better than non-predictive scheduling by ensuring that AoI spikes are minimized during handover events. This advantage is particularly important in satellite constellations with frequent handovers, such as Low Earth Orbit (LEO) networks.

4.2.2 Energy-Aware Algorithms

Energy-aware algorithms optimize AoI by adjusting transmission frequency based on energy availability. Satellites powered by solar energy are particularly affected by fluctuations in energy availability as they move in and out of direct sunlight. By dynamically adjusting transmission schedules based on available energy, these algorithms enable satellite networks to maintain a balance between AoI performance and energy conservation.

Key benefits of energy-aware algorithms include:

- **Optimized transmission frequency**: Satellites can transmit more frequently when energy levels are high (e.g., when in direct sunlight) and reduce transmission frequency during periods of low energy availability (e.g., when in Earths shadow).
- **Extended satellite lifespan**: By conserving energy when necessary, energy-aware algorithms prolong the operational lifespan of satellites, ensuring they can continue to perform optimally over time.
- **Lower operational costs**: Reducing energy consumption directly translates to lower operational costs, as satellites require fewer interventions and energy reserves can be conserved for critical operations.

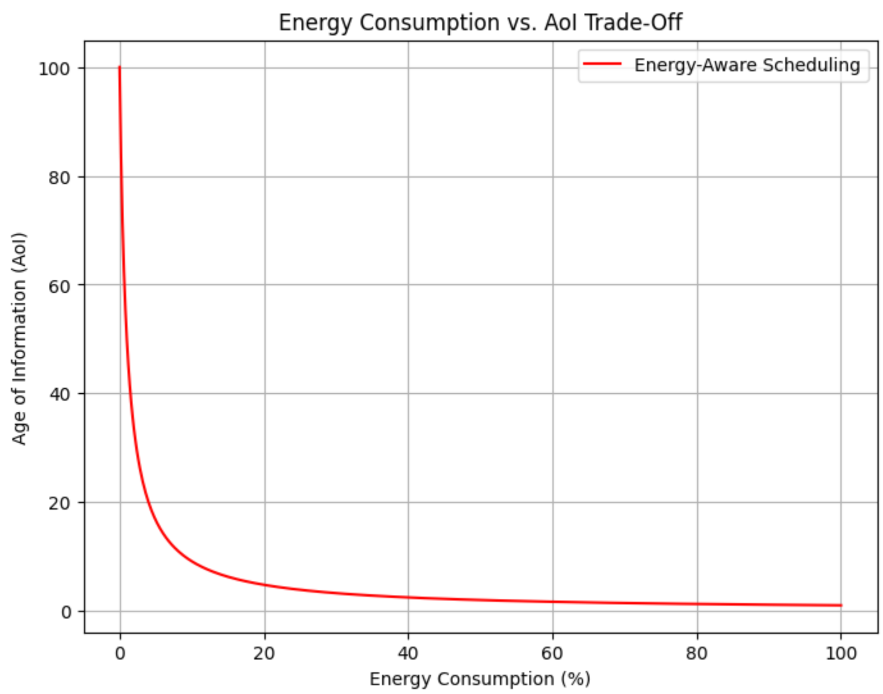

Figure 4.4: Energy Consumption vs. AoI Trade-Off in Energy-Aware Algorithms.

Figure 4.4 illustrates the trade-off between energy consumption and AoI. As energy-aware algorithms reduce the frequency of updates during low-energy periods, AoI may increase temporarily, but energy consumption is optimized, ensuring that resources are available for critical updates when needed.

4.2.3 Combined Approach: Predictive and Energy-Aware Scheduling

The integration of predictive scheduling with energy-aware algorithms creates a powerful mechanism for reducing AoI while optimizing energy usage. By leveraging both predictive models and real-time energy data, satellite networks can prioritize updates at the most opportune times while conserving energy during low-activity periods. This combined approach ensures that AoI is minimized without overburdening the satellites energy resources [37].

4.3 Multi-Satellite Cooperation and Distributed Optimization

In large satellite constellations, such as those used by companies like Starlink and OneWeb, multi-satellite cooperation is essential for ensuring low Age of Information (AoI) and maximizing communication efficiency. Multi-satellite cooperation allows satellites to work together to distribute the transmission load, reducing the frequency of redundant updates and optimizing resource utilization across the network.

4.3.1 Impact on Energy Consumption

One of the main advantages of multi-satellite cooperation is its potential to reduce energy consumption across the network. By distributing communication tasks among multiple satellites, the network can conserve energy by avoiding redundant transmissions and minimizing the workload on individual satellites. [16, 51]

- Satellites can share real-time data about their energy levels and communication windows, allowing the network to prioritize transmissions from satellites with higher energy reserves.
- When a satellite is running low on energy, nearby satellites can take over its communication duties, reducing the strain on the energy-depleted satellite and ensuring continuous data flow.

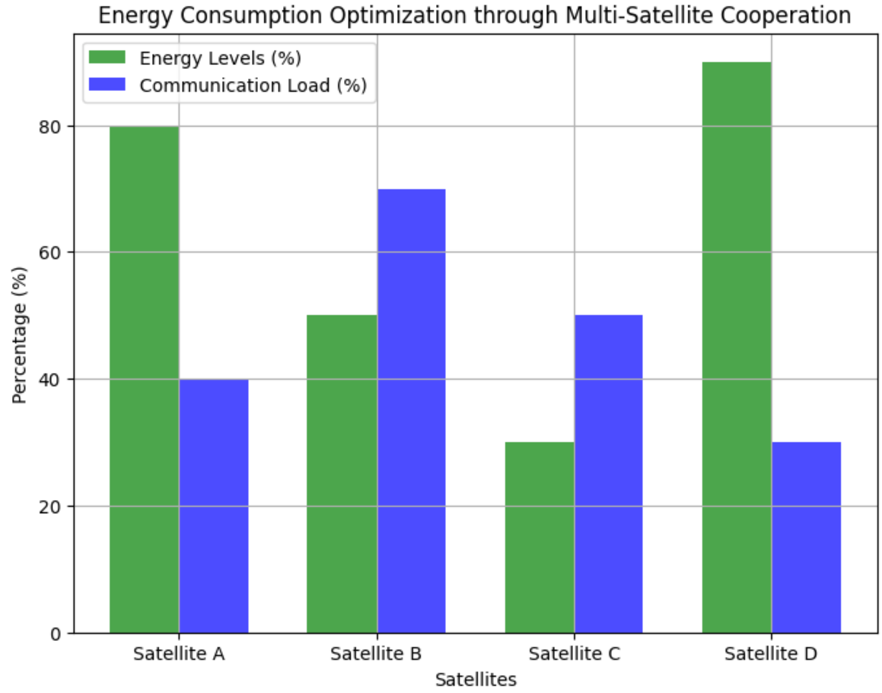

Figure 4.5: Energy Consumption Optimization through Multi-Satellite Cooperation.

As shown in Figure 4.5, multi-satellite cooperation allows for a more efficient distribution of energy consumption across the network. Satellites with high energy reserves take on a larger portion of the communication load, while satellites with lower energy reserves can conserve their resources for critical tasks.

4.3.2 Improved Communication Efficiency

Multi-satellite cooperation also plays a crucial role in improving communication efficiency by reducing the frequency of handovers and ensuring continuous data transmission to ground stations. By sharing information about their positions and communication windows, satellites can coordinate their transmission schedules to avoid periods of network congestion and reduce AoI across the network.

Key advantages of distributed optimization in multi-satellite cooperation include:

- **Improved handover efficiency**: Satellites can hand off communication tasks to one another seamlessly, ensuring continuous data transmission without introducing delays or AoI spikes.

- **Optimized resource allocation**: Distributed optimization algorithms allow each satellite to independently adjust its transmission strategy based on real-time network conditions, ensuring efficient use of bandwidth and communication resources.
- **Reduced network congestion**: By dynamically adjusting transmission schedules to avoid simultaneous transmissions, the network can reduce the risk of congestion and improve overall communication efficiency. [37, 29, 24]

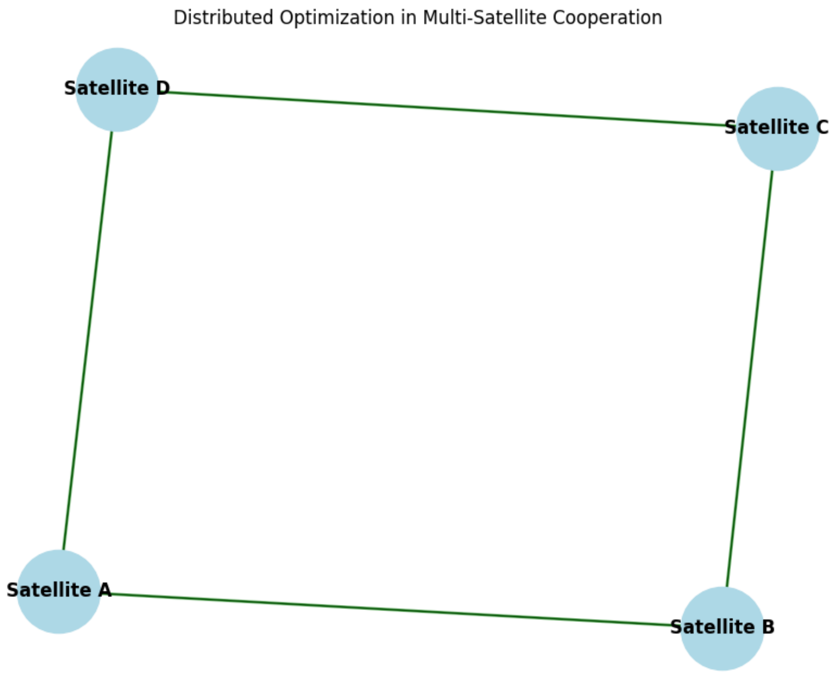

Figure 4.6: Distributed Optimization in Multi-Satellite Cooperation.

Figure 4.6 illustrates how distributed optimization algorithms allow satellites to independently manage their transmission schedules, avoiding congestion and optimizing the use of communication resources. This approach is particularly effective in large-scale satellite constellations, where frequent handovers and dynamic network conditions can create communication bottlenecks.

4.3.3 Advantages of Multi-Satellite Cooperation for AoI Minimization

By enabling cooperation between satellites, the network can minimize AoI while reducing energy consumption and optimizing communication efficiency. The combined use of multi-satellite cooperation and distributed optimization algorithms ensures that the network remains resilient in the face of changing environmental and operational conditions [50].

- Satellites can coordinate their update schedules to minimize AoI across the network, ensuring that critical information is always available in real-time.
- Distributed optimization ensures that satellites can independently adjust their transmission strategies based on real-time data, reducing the risk of network congestion and maximizing communication efficiency.

In conclusion, multi-satellite cooperation and distributed optimization represent a powerful approach to minimizing AoI in satellite constellations, particularly in energy-constrained environments where efficient resource allocation is critical. The integration of these techniques allows satellite networks to maintain real-time communication while reducing energy consumption and optimizing the use of available communication resources.

4.4 Combining Predictive Scheduling and Multi-Satellite Cooperation

The integration of predictive scheduling with multi-satellite cooperation has proven to be a highly effective strategy for minimizing Age of Information (AoI) in satellite networks. By leveraging the strengths of both approaches, satellite networks can significantly reduce the frequency of AoI spikes while ensuring continuous data flow to ground stations. This combination allows satellite constellations to operate efficiently even under challenging conditions, such as frequent handovers and fluctuating energy availability.

4.4.1 Advantages of the Combined Approach

The combined use of predictive scheduling and multi-satellite cooperation offers several key advantages for reducing AoI and improving overall network performance:

- **Minimized AoI spikes during handovers**: Predictive scheduling allows satellites to transmit updates just before handovers, while multi-satellite cooperation ensures that nearby satellites take over the transmission duties, reducing the risk of prolonged disconnection periods.
- **Improved energy efficiency**: Satellites with higher energy reserves can prioritize critical updates, while energy-depleted satellites can conserve resources without compromising the overall performance of the network.

- **Seamless coordination of updates**: By sharing real-time information about their positions and energy levels, satellites can coordinate their update schedules to ensure that critical information is transmitted with minimal delay.

This approach is particularly valuable in large-scale constellations, where hundreds or even thousands of satellites must work together to maintain continuous global coverage. As the number of satellites in a constellation increases, the benefits of predictive scheduling and multi-satellite cooperation become more pronounced, as the network can distribute the communication load more effectively and ensure that AoI remains low across the entire system.

4.4.2 AoI Performance in Large-Scale Constellations

To evaluate the effectiveness of the combined approach, we conducted a series of simulations to compare AoI performance in large-scale satellite constellations with and without the use of predictive scheduling and multi-satellite cooperation. The results indicate that the combined approach significantly reduces AoI across a variety of scenarios, including different satellite orbits, handover frequencies, and energy constraints [30].

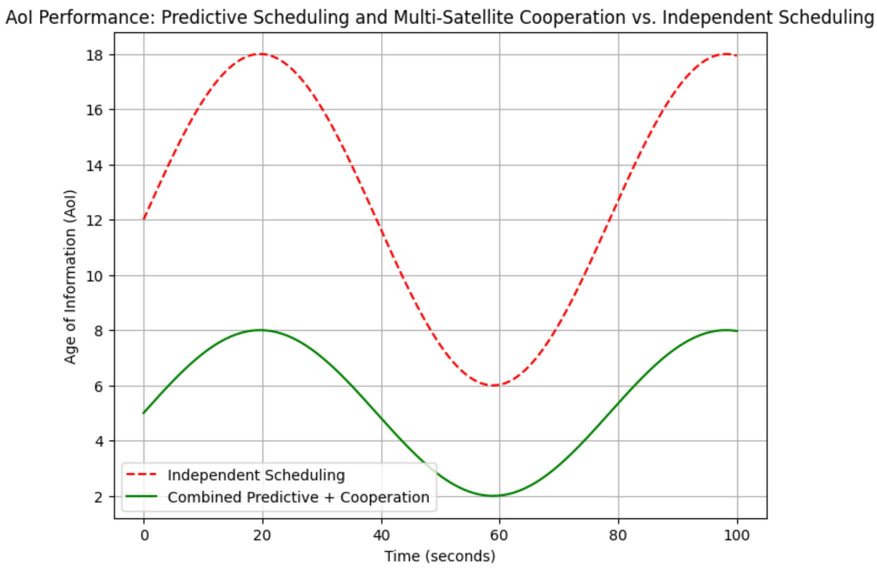

Figure 4.7: AoI Performance: Predictive Scheduling and Multi-Satellite Cooperation vs. Independent Scheduling.

Figure 4.7 compares the AoI performance of a network using the combined approach (predictive scheduling and multi-satellite cooperation) with that of a network relying solely on independent scheduling by individual satellites. The results show that the combined approach significantly reduces AoI spikes, particularly during periods of frequent handovers.

4.4.3 Energy and Bandwidth Optimization

In addition to improving AoI performance, the combined approach optimizes the use of energy and bandwidth resources. By allowing satellites to cooperate and share communication tasks, the network can reduce the frequency of redundant updates, freeing up bandwidth for more critical transmissions. Furthermore, energy-aware scheduling ensures that satellites can conserve energy during low-activity periods without compromising the timeliness of critical updates [49].

- Satellites with higher energy reserves can take on a larger portion of the communication load, allowing energy-depleted satellites to conserve resources.
- Predictive scheduling allows satellites to prioritize critical updates before handovers, ensuring that the latest information is transmitted before the satellite passes out of range.

The combination of predictive scheduling and multi-satellite cooperation is particularly effective in energy-constrained environments, such as Low Earth Orbit (LEO) satellite networks. By optimizing both energy usage and AoI performance, this approach allows satellite networks to operate efficiently over extended periods without requiring frequent maintenance or intervention.

4.4.4 Summary of Findings

Our analysis shows that the integration of predictive scheduling with multi-satellite cooperation provides a robust solution for minimizing AoI and optimizing network performance in satellite constellations. The key findings from our simulations are as follows:

- Predictive scheduling and multi-satellite cooperation significantly reduce AoI spikes during handover events.
- The combined approach improves energy efficiency by distributing communication tasks across multiple satellites, allowing energy-depleted satellites to conserve resources.
- AoI performance is improved across a wide range of scenarios, including varying satellite orbits, handover frequencies, and energy constraints.

These findings demonstrate the potential of predictive scheduling and multi-satellite cooperation to revolutionize satellite network operations, enabling more efficient communication and reducing the frequency of AoI spikes in real-time applications.

4.5 Real-World Applications and Case Studies

The optimization of Age of Information (AoI) is not just a theoretical concept but plays a vital role in several real-world satellite communication networks. This section explores key real-world applications where AoI optimization is crucial, including large-scale satellite constellations, disaster monitoring systems, and global Internet services. Additionally, we review case studies that highlight the effectiveness of predictive scheduling and multi-satellite cooperation.

4.5.1 Large-Scale Satellite Constellations (e.g., Starlink and OneWeb)

One of the most prominent real-world applications of AoI optimization is in large-scale satellite constellations such as **Starlink** and **OneWeb**. These networks consist of thousands of low Earth orbit (LEO) satellites, providing global Internet coverage with minimal latency. In such systems, maintaining low AoI is critical to ensuring that data remains fresh and that users experience minimal delay in communication [42].

Key benefits of AoI optimization in large-scale constellations include:

- **Reduced latency for Internet services**: Low AoI ensures that users receive the most up-to-date information with minimal delay, improving the quality of service for real-time applications like video calls and gaming.
- **Enhanced satellite handover performance**: Predictive scheduling reduces the impact of frequent handovers, allowing continuous communication without significant spikes in AoI [31].
- **Optimized bandwidth allocation**: By minimizing redundant updates and efficiently distributing communication tasks among satellites, the network can allocate bandwidth more effectively, reducing congestion and improving overall performance [13].

As shown in Figure 4.8, the implementation of AoI optimization techniques, such as predictive scheduling and multi-satellite cooperation, has a significant impact on latency and bandwidth utilization in large-scale constellations like Starlink.

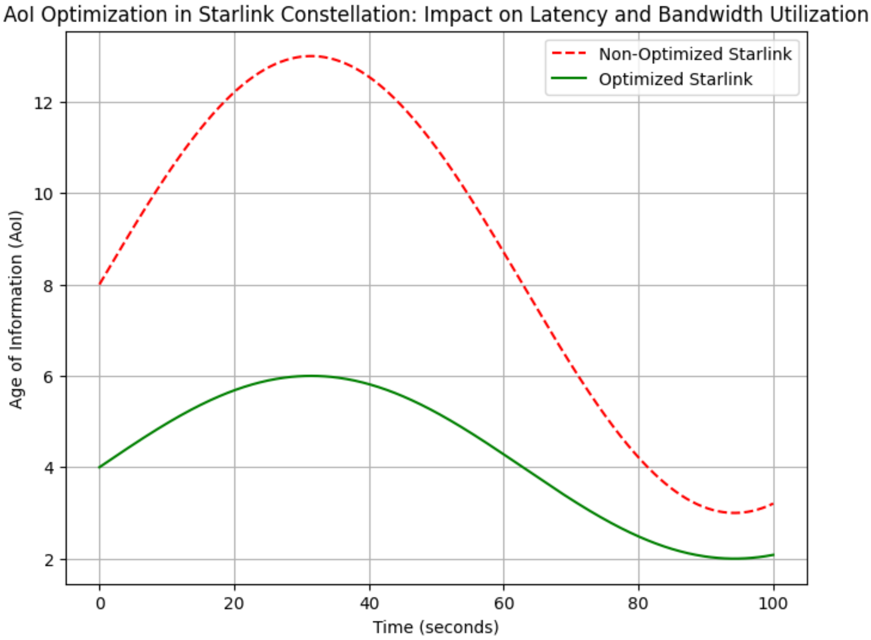

Figure 4.8: AoI Optimization in Starlink Constellation: Impact on Latency and Bandwidth Utilization.

4.5.2 Disaster Monitoring Systems

Another critical application of AoI optimization is in satellite-based **disaster monitoring systems**. During natural disasters, such as wildfires, floods, or hurricanes, real-time information is essential for coordinating rescue efforts and minimizing damage. In such situations, maintaining low AoI ensures that decision-makers have access to the freshest data, enabling them to respond more effectively [1, 2].

Key advantages of AoI optimization in disaster monitoring include:

- **Real-time updates for emergency responders**: Low AoI ensures that critical information, such as the location and intensity of a wildfire or flood, is transmitted in real-time, enabling emergency responders to take swift action [48].
- **Optimized resource allocation**: By minimizing AoI, satellite networks can prioritize the transmission of high-value data, ensuring that rescue teams receive the most relevant information without delays [31].
- **Improved coordination between agencies**: Multi-satellite cooperation enables different agencies to access real-time updates, improving coordination and reducing response times [4].

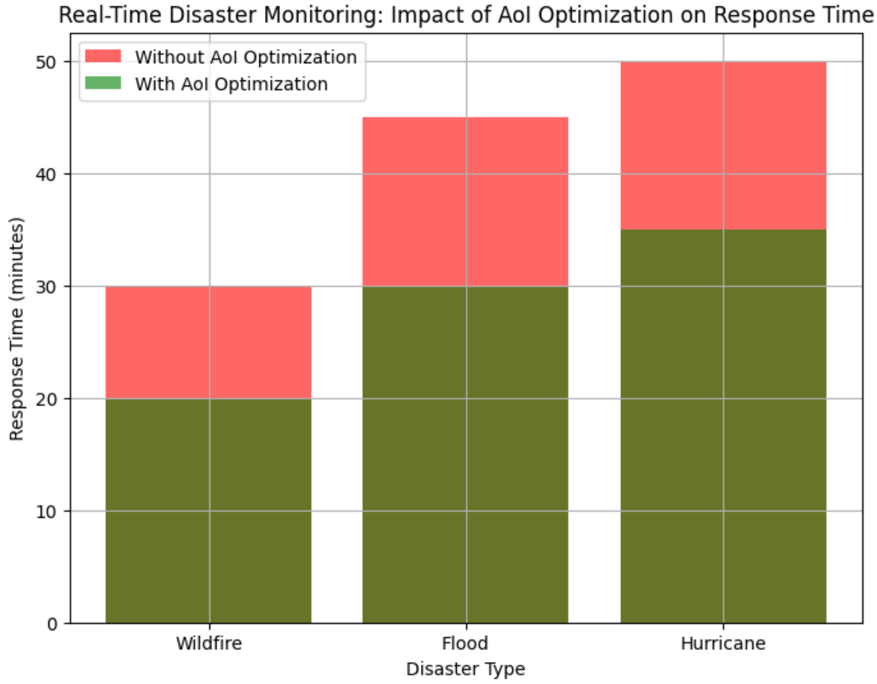

Figure 4.9: Real-Time Disaster Monitoring: Impact of AoI Optimization on Response Time.

Figure 4.9 demonstrates how AoI optimization can significantly reduce response times during disaster situations, ensuring that emergency responders have access to real-time data [1].

4.5.3 Case Study: Global Internet Service Deployment

The deployment of global Internet services via satellite, particularly in remote and underserved regions, presents a compelling case study for the effectiveness of AoI optimization. One such example is the deployment of Internet services in rural and remote areas by **Project Loon** [36] (a former initiative by Google) and satellite constellations like **OneWeb**. These services rely on low AoI to provide users with real-time access to the Internet, enabling remote communities to access vital online resources such as telemedicine, education, and government services [28].

The case study highlights the following benefits of AoI optimization:

- **Low-latency Internet access**: By minimizing AoI, satellite networks can provide remote communities with low-latency access to the Internet, enabling real-time communication and reducing the digital divide [31].

- **Efficient use of satellite resources**: Multi-satellite cooperation ensures that communication tasks are distributed efficiently, reducing energy consumption and prolonging the operational lifespan of satellites [19].
- **Improved service quality**: The implementation of AoI optimization techniques ensures that users experience a seamless and reliable connection, improving the overall quality of service [7].

In summary, the real-world applications of AoI optimization in satellite networks, from large-scale constellations to disaster monitoring systems, demonstrate its critical importance for ensuring real-time data transmission and improving overall network performance. The case studies reviewed in this section highlight the potential for AoI optimization to transform satellite communication systems, providing users with more reliable and efficient services [28, 31, 19, 7].

5 Conclusion

5.1 Summary of Key Findings and Contributions

The primary goal of this thesis was to explore and optimize the Age of Information (AoI) in satellite networks, with a particular focus on Low Earth Orbit (LEO) satellite constellations. Throughout the research, we employed several techniquessuch as predictive scheduling, multi-satellite cooperation, and energy-aware algorithmsto minimize AoI while ensuring efficient use of energy and communication resources.

The key findings of this research can be summarized as follows:

- **Effectiveness of Predictive Scheduling:** Predictive scheduling significantly reduces AoI during satellite handovers by ensuring that critical updates are transmitted just before satellites pass out of communication range. This technique was particularly effective in large-scale constellations such as **Starlink** and **OneWeb**, where frequent handovers occur due to the fast movement of satellites.

- **Multi-Satellite Cooperation:** The use of multi-satellite cooperation strategies, where satellites coordinate their transmission schedules and share communication resources, has proven to be an effective method for reducing AoI and conserving energy. By distributing communication tasks among satellites based on their energy availability and communication windows, the overall network performance improves.

- **Energy-Aware Algorithms:** Energy-aware algorithms that dynamically adjust the update frequency based on the satellite's available energy have shown great potential for improving the longevity and efficiency of satellite systems. By scheduling updates based on energy availability, satellites can maintain a balance between minimizing AoI and conserving energy resources.

- **Real-Time Applications:** The findings also demonstrate the importance of AoI optimization for real-time applications, such as disaster monitoring and global Internet services. In these applications, maintaining low AoI ensures that users and responders receive up-to-date information, leading to improved decision-making and communication efficiency.

These contributions highlight the importance of AoI as a critical performance metric in satellite networks and provide a foundation for future research aimed at further optimizing data freshness and communication efficiency in non-terrestrial networks.

5.2 Discussion of Implications

The research presented in this thesis has significant implications for the design and optimization of satellite networks, particularly in the context of large-scale constellations and real-time applications. One of the most important findings is the role that predictive scheduling and multi-satellite cooperation can play in minimizing AoI across satellite systems. These techniques are especially important as the demand for low-latency, real-time communication continues to grow.

For satellite constellations like **Starlink** and **OneWeb**, AoI optimization ensures that real-time services such as video calls, telemedicine, and disaster response are more reliable and efficient. By minimizing the time it takes for data to become stale, AoI optimization enhances the quality of service for users in remote and underserved areas, where terrestrial infrastructure may be lacking. This finding is particularly relevant in the context of global efforts to bridge the digital divide and bring high-speed Internet access to rural regions.

Additionally, the introduction of energy-aware scheduling has practical implications for the long-term sustainability of satellite networks. As LEO satellites typically have limited energy resources, optimizing update schedules to align with available energy levels ensures that satellite lifespans are prolonged and that energy is used efficiently. This approach aligns with ongoing efforts to develop more sustainable and energy-efficient satellite communication systems.

The implications of this research extend beyond traditional satellite systems to broader applications in the **Internet of Things (IoT)** and non-terrestrial networks, where AoI plays a crucial role in maintaining data freshness in a range of applications. From autonomous vehicles to smart cities, the ability to deliver fresh data in real-time will continue to be a critical factor in the success of future communication networks [40].

5.3 Future Research Directions

While this thesis has provided several key contributions to the field of AoI optimization in satellite networks, there remain numerous avenues for future research. Some potential directions for further study include:

5.3.1 Integration of Machine Learning with AoI Optimization

One promising area of future research is the integration of **machine learning (ML) algorithms** with AoI optimization. Machine learning models could be used to predict satellite handovers, communication windows, and energy availability with greater accuracy, allowing for even more efficient update scheduling. By leveraging historical data and real-time telemetry, ML algorithms could further optimize transmission schedules, reducing AoI and improving overall network performance [37, 3].

5.3.2 Advanced Energy Harvesting Techniques

Future research could also explore the integration of **advanced energy harvesting technologies** into satellite networks. As satellites are increasingly being equipped with solar panels and other energy-harvesting mechanisms, understanding how these technologies can be optimized to maintain low AoI in energy-constrained environments will be critical. Research into new materials and energy storage techniques could help extend the operational lifespans of LEO satellites while maintaining low AoI [20].

5.3.3 Expanding AoI Research to Other Non-Terrestrial Networks

Finally, future work should consider expanding AoI research to other types of **non-terrestrial networks** beyond satellite systems. This could include networks involving drones, high-altitude platforms (HAPs), and other types of aerial communication systems. Understanding how AoI behaves in these networks, particularly in dynamic and energy-constrained environments, could lead to broader applications of AoI optimization techniques [44].

In conclusion, the work presented in this thesis represents an important step toward optimizing AoI in satellite networks [34], but there is still much more to explore. As communication technologies continue to evolve, the need for fresh, up-to-date data will become even more critical, making AoI optimization a key area of focus for future research.

References

[1] Mohamed A Abd-Elmagid, Nikolaos Pappas, and Harpreet S Dhillon. "On the Role of Age of Information in the Internet of Things". In: *IEEE Communications Magazine* 57.12 (2019), pp. 72–77.

[2] Mohamed S. Abdalzaher, Moez Krichen, and Francisco Falcone. "Emerging technologies and supporting tools for earthquake disaster management: A perspective, challenges, and future directions". In: *Progress in Disaster Science* 23 (2024), p. 100347. ISSN: 2590-0617. DOI: https://doi.org/10.1016/j.pdisas.2024.100347. URL: https://www.sciencedirect.com/science/article/pii/S2590061724000371.

[3] Mohamed Abdel-Kader et al. "A Machine Learning-Based Uplink Resource Allocation Technique for Mixed Traffic in Non-Terrestrial Networks". In: *2024 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*. 2024, pp. 23–29. DOI: 10.1109/BlackSeaCom61746.2024.10646311.

[4] Mohamed Aboualola et al. "Edge Technologies for Disaster Management: A Survey of Social Media and Artificial Intelligence Integration". In: *IEEE Access* 11 (2023), pp. 73782–73802. DOI: 10.1109/ACCESS.2023.3293035.

[5] Aynur Cemre Aka and Leonardo Badia. "A Zero-Sum Game of Age of Information Over a Finite Horizon Between Sensor and Adversary". In: *Proc. Int. Artif. Intell. Data Proc. Symposium (IDAP)*. 2024, pp. 1–5.

[6] Amazon. *Project Kuiper*. https://www.aboutamazon.com/news/innovation-at-amazon/project-kuiper. 2024.

[7] M. Mahdi Azari et al. "Evolution of Non-Terrestrial Networks From 5G to 6G: A Survey". In: *IEEE Communications Surveys and Tutorials* 24.4 (2022), pp. 2633–2672. DOI: 10.1109/COMST.2022.3199901.

[8] Leonardo Badia. “A Markov analysis of selective repeat ARQ with variable round trip time”. In: *IEEE Communications Letters* 17.11 (2013), pp. 2184–2187.

[9] Leonardo Badia. “Age of information from two strategic sources analyzed via game theory”. In: *Proc. IEEE Int. Workshop Comp. Aided Modeling Design Commun. Links Netw. (CAMAD)*. 2021, pp. 1–6.

[10] Leonardo Badia, Elisa Feltre, and Elvina Gindullina. “A Markov Model Accounting for Charge Recovery in Energy Harvesting Devices”. In: *2017 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*. 2017, pp. 1–6. DOI: `10.1109/WCNCW.2017.7919072`.

[11] Leonardo Badia and Andrea Munari. “Exogenous Update Scheduling in the Industrial Internet of Things for Minimal Age of Information”. In: *IEEE Transactions on Industrial Informatics* (2025).

[12] Leonardo Badia, Andrea Zanella, and Michele Zorzi. “A game of ages for slotted ALOHA with capture”. In: *IEEE Trans. Mob. Comput.* 23.5 (2024), pp. 4878–4889.

[13] Leonardo Badia, Andrea Zanella, and Michele Zorzi. “Game theoretic analysis of age of information for slotted ALOHA access with capture”. In: *IEEE INFOCOM 2022-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE. 2022, pp. 1–6.

[14] Leonardo Badia et al. “Analysis of an automatic repeat request scheme addressing long delay channels”. In: *Proc. IEEE Int. Conf. Adv. Inf. Netw. Appl. Workshops*. 2009, pp. 1142–1147.

[15] Leonardo Badia et al. “Status update scheduling in remote sensing under variable activation and propagation delays”. In: *Ad Hoc Networks* 163 (2024), p. 103583.

[16] Xiaoyu Chen et al. “Data-Driven Collaborative Scheduling Method for Multi-Satellite Data-Transmission”. In: *Tsinghua Science and Technology* 29.5 (2024), pp. 1463–1480. DOI: `10.26599/TST.2023.9010131`.

[17] Federico Chiariotti and Leonardo Badia. “Strategic age of information aware interaction over a relay channel”. In: *IEEE Transactions on Communications* 72.1 (2024), pp. 101–116.

[18] Trung Q. Duong et al. “Machine Learning-Aided Real-Time Optimized Multibeam for 6G Integrated Satellite-Terrestrial Networks: Global Coverage for Mobile Services”. In: *IEEE Network* 37.2 (2023), pp. 86–93. DOI: 10.1109/MNET.003.2200275.

[19] Sunyue Geng et al. “An agent-based clustering framework for reliable satellite networks”. In: *Reliability Engineering and System Safety* 212 (2021), p. 107630. ISSN: 0951-8320. DOI: https://doi.org/10.1016/j.ress.2021.107630. URL: https://www.sciencedirect.com/science/article/pii/S095183202100171X.

[20] Elvina Gindullina, Leonardo Badia, and Deniz Gündüz. “Age-of-information with information source diversity in an energy harvesting system”. In: *IEEE Transactions on Green Communications and Networking* 5.3 (2021), pp. 1529–1540.

[21] Umut Gueloglu, Leonardo Badia, and Andrea Munari. In: *Proc. IEEE Int. Workshop Comp. Aided Modeling Design Commun. Links Netw. (CAMAD)*. 2024, pp. 1–6. URL: https://elib.dlr.de/206833/.

[22] Francesco Guidolin et al. “A cooperative scheduling algorithm for the coexistence of fixed satellite services and 5G cellular network”. In: *Proc. IEEE Int. Conf. Commun. (ICC)*. IEEE. 2015, pp. 1322–1327.

[23] Mutasem Q. Hamdan et al. “Recent Advances in Machine Learning for Network Automation in the O-RAN”. In: *Sensors* 23.21 (2023). ISSN: 1424-8220. DOI: 10.3390/s23218792.

[24] Hayder Al-Hraishawi et al. “A Survey on Nongeostationary Satellite Systems: The Communication Perspective”. In: *IEEE Communications Surveys and Tutorials* 25.1 (2023), pp. 101–132. DOI: 10.1109/COMST.2022.3197695.

[25] Sanjit Kaul, Roy Yates, and Marco Gruteser. “Real-time status: How often should one update?” In: *2012 Proceedings IEEE INFOCOM*. IEEE. 2012, pp. 2731–2735.

[26] Philippe Krajsic et al. “Trends, Advancements and Challenges in Intelligent Optimization in Satellite Communication”. In: *arXiv preprint arXiv:2410.03674* (2024).

[27] Dongqing Li et al. “Towards Age-Optimal Transmission in Satellite-Integrated IoT: A Two-Layer Coding Approach”. In: *IEEE Transactions on Vehicular Technology* 72.1 (2023), pp. 1137–1148. DOI: 10.1109/TVT.2022.3205625.

[28] Yuanjie Li et al. “A Networking Perspective on Starlink’s Self-Driving LEO Mega-Constellation”. In: *Proceedings of the 29th Annual International Conference on Mobile Computing and Networking*. ACM MobiCom ’23. Madrid, Spain: Association for Computing Machinery, 2023. ISBN: 9781450399906. DOI: 10.1145/3570361.3592519.

[29] Mingjun Liao et al. “Information Freshness Optimal Resource Allocation for LEO-Satellite Internet of Things”. In: *IEEE Internet of Things Journal* 11.10 (2024), pp. 17372–17387. DOI: 10.1109/JIOT.2024.3357869.

[30] Haotian Liu et al. “A Multi-Agent Deep Reinforcement Learning-Based Handover Scheme for Mega-Constellation Under Dynamic Propagation Conditions”. In: *IEEE Transactions on Wireless Communications* 23.10 (2024), pp. 13579–13596. DOI: 10.1109/TWC.2024.3407358.

[31] Yanwu Lu et al. “Analysis of Age of Information in Non-terrestrial Networks”. In: (2023), pp. 239–244.

[32] Wenkai Lv et al. “Energy-efficient and QoS-aware computation offloading in GEO/LEO hybrid satellite networks”. In: *Remote Sensing* 15.13 (2023), p. 3299.

[33] S. Mondal, S. Al-Rubaye, and A. Tsourdos. “Handover prediction for aircraft dual connectivity using model predictive control”. In: *IEEE Access* 9 (2021), pp. 58759–58770.

[34] Andrea Munari and Leonardo Badia. “Satellite intermittent connectivity and its impact on age of information for finite horizon scheduling”. In: *Proc. Signal Proc. Space Commun. Workshop*. 2025.

[35] Andrea Munari and Leonardo Badia. “The role of feedback in AoI optimization under limited transmission opportunities”. In: *Proc. IEEE Global Communications Conference*. 2022, pp. 1972–1977.

[36] Lavina Nagpal and Krishna Samdani. “Project Loon: Innovating the connectivity worldwide”. In: *2017 2nd IEEE International Conference on Recent Trends in Electronics, Information and Communication Technology (RTEICT)*. 2017, pp. 1778–1784. DOI: 10.1109/RTEICT.2017.8256905.

[37] Quynh Tu Ngo et al. “Timeliness of Information in 5G Nonterrestrial Networks: A Survey”. In: *IEEE Internet of Things Journal* 11.21 (2024), pp. 34652–34675. DOI: 10.1109/JIOT.2024.3407105.

[38] Zhisheng Niu et al. “Space-air-ground integrated vehicular network for connected and automated vehicles: Challenges and solutions”. In: *Intelligent and Converged Networks* 1.2 (2020), pp. 142–169. DOI: 10.23919/ICN.2020.0009.

[39] OneWeb. *OneWeb*. https://www.oneweb.world/. 2024.

[40] Michele Rossi, Leonardo Badia, and Michele Zorzi. “Exact statistics of ARQ packet delivery delay over Markov channels with finite round-trip delay”. In: *Proc. IEEE Global Communications Conference*. Vol. 6. 2003, pp. 3356–3360.

[41] Satellite Today. *LEO Satellite Systems: An Overview*. https://www.satellitetoday.com/. 2024.

[42] Shahriar Shirvani Moghaddam. “The Past, Present, and Future of the Internet: A Statistical, Technical, and Functional Comparison of Wired/Wireless Fixed/Mobile Internet”. In: *Electronics* 13.10 (2024). ISSN: 2079-9292.

[43] SpaceX. *Starlink*. https://www.starlink.com/. 2024.

[44] Xiaonan Wang, Yang Guo, and Yuan Gao. “Unmanned Autonomous Intelligent System in 6G Non-Terrestrial Network”. In: *Information* 15.1 (2024). ISSN: 2078-2489. DOI: 10.3390/info15010038.

[45] Ying Wang et al. “A Review on Wireless Networked Control System: The Communication Perspective”. In: *IEEE Internet of Things Journal* 11.5 (2024), pp. 7499–7524. DOI: 10.1109/JIOT.2023.3342032.

[46] Roy D Yates et al. “Age of information: An introduction and survey”. In: *IEEE Journal on Selected Areas in Communications* 39.5 (2021), pp. 1183–1210.

[47] Alberto Zancanaro, Giulia Cisotto, and Leonardo Badia. “Modeling value of information in remote sensing from correlated sources”. In: *Computer Communications* 203 (2023), pp. 289–297.

[48] Fan Zeng, Chuan Pang, and Huajun Tang. “Sensors on the Internet of Things Systems for Urban Disaster Management: A Systematic Literature Review”. In: *Sensors* 23.17 (2023). ISSN: 1424-8220. DOI: 10.3390/s23177475.

[49] Lingchao Zeng et al. “A Heterogeneous Multi-Satellite Dynamic Mission Planning Method Based on Metaheuristic Algorithms”. In: *Electronics* 13.22 (2024). ISSN: 2079-9292. DOI: 10.3390/electronics13224353.

[50] Zixuan Zheng, Jian Guo, and Eberhard Gill. "Distributed Agent-based Approaches for Multi-Satellite System Limited Coordination Problem". In: *2018 SpaceOps Conference*. 2018, p. 2391.

[51] Zixuan Zheng, Jian Guo, and Eberhard Gill. "Onboard mission allocation for multi-satellite system in limited communication environment". In: *Aerospace Science and Technology* 79 (2018), pp. 174–186. ISSN: 1270-9638. DOI: https://doi.org/10.1016/j.ast.2018.05.022.