Modeling Weighted Average Age of Information (WAAI) in Non-Symmetric Networks:Practical Scheduling Approaches

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DEDICATION

This thesis is dedicated to my family, whose unwavering support and encouragement have been the foundation of my success. To my parents, for instilling in me the value of education and perseverance, and to my friends and mentors, who have inspired and guided me throughout this journey. Your belief in my potential has been my greatest motivation.

I also dedicate this work to all those who pursue knowledge with passion and determination, especially those who face the hardship of financial barriers and cannot afford the education they deserve. May this work stand as a testament to the idea that knowledge should be accessible to all, regardless of circumstance, and that together we can work towards a future where education is a right, not a privilege.

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Abstract

In the ever-expanding environment of the Internet-of-Things (IoT), multiple sensors/- sources simultaneously send their updated information to the destination or sink. To ensure the updated data availability, a new concept Age of Information (AoI) has emerged as a key metric, representing the time elapsed since the last update from a specific sensor or source was received at the destination. A lower AoI indicates fresherinformation, which is crucial for maintaining data relevance. The minimum the AoI, the freshest will be the information, and vice versa. It becomes more difficult to minimize AoI when multiple users use multiple hops under non-symmetric network conditionsto send their data to some remote destination. This thesis investigates average AoI in a non-symmetric multi-user multi-hop network. To manage the non-symmetry complexity imposed by the multi-user multi-hop scenario, only one channel is assumed for data transfer, from the source to the sink. Depending on the arrival time, each data packet is assigned a specific weight. These assigned weights serve as a reference in minimization of the AoI. After assigning proper weights, next we schedule these weighted packets. For scheduling purposes, three scheduling policies, i.e., first source first serve (FSFS), earliest served first serve (ESFS), and single buffer with replacement (SBR), are implemented. The outputs of these policies are compared using the Cumulative Distribution Function (CDF), Sum of age of information, and age violation probability. The results demonstrate that the Earliest Served First Served policy consistently yields consistently yields minimum age of information in all considered aspects.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AoI - Age of Information
MCS - Military College of Signals
NUST – National University of Science and Technology
FSFS - First Source First Serve
ESFS - Earliest Served First Serve
SBR - Single Buffer with Replacement
WSN - Wireless Sensor Network
IoT - Internet of Things
N - Number of Sources
λ - Packet arrival intensity
μ - Service Times
CDF - Cumulative Density Function
τ – *Age Threshold*

Chapter 1

Introduction

1.1 Background

Internet-of-things (IoT) is a vast network of interconnected devices that communicate with each other through wired or wireless mediums, enabling the exchange of valuable information between various systems. This concept has found applications in almost every industry, fundamentally transforming traditional practices and revolutionizing the way we think about technology and communication. In the past, communication systems were much more limited, e.g., with old telephone lines, if one person was using the line, all other users had to wait until the first person finished their call before they could use the line themselves. This created significant delays and inefficiencies, especially in situations where communication was critical. However, with the advent of the Internet, such limitations have been virtually eliminated. The IoT allows multiple devices to share the same communication link simultaneously, enabling a large number of devices to access and exchange data without any delay. This ability to handle multiple users and devices simultaneously is one of the most significant advancements brought about by IoT. However, it also introduces a new set of challenges. As the number of connected devices grows, so does the volume of data that is generated. The network is inundated with a massive number of data packets or signals, all of which need to be transmitted and processed efficiently. This increase in data traffic can create potential bottlenecks and challenges in maintaining smooth communication.

To manage this overwhelming influx of data, the concept of the Age of Information (AoI) has become increasingly important. AoI is a metric that measures the freshness or timeliness of data by tracking how long the date has taken since the last update from a specific device or user till it reaches its destination. In the context of IoT, AoI helps prioritize and schedule the transmission of data packets, ensuring that the most critical and time-sensitive information is delivered promptly while also maintaining smooth and uninterrupted communication for all devices/users. In practical terms,

the integration of AoI in IoT systems means that the network can dynamically adjust to the varying demands of different devices. Similarly, in industrial settings, AoI can ensure that data from machines requiring immediate attention is processed faster than routine updates, thereby improving efficiency and safety.
The AoI-driven scheduling in IoT networks can further be improved through the use of advanced algorithms and machine-learning techniques. These technologies can analyze data patterns, predict potential network congestion, and adjust the scheduling of data packets in real-time scenarios to optimize their performance. This not only ensures that all users have a seamless communication experience but will also help in the efficient utilization of network resources.
In conclusion, the Internet of Things has dramatically expanded the possibilities for interconnected communication, allowing multiple devices to share the same network and exchange vast amounts of data without the delays that plagued earlier systems. However, this increased data flow necessitates effective management strategies, such as the application of age-of-information (AoI) to maintain the efficiency and reliability of communication networks. Through the use of AoI and advanced scheduling techniques, IoT systems can continue to provide seamless, interruption-free communication for all users, even as the volume of data continues to grow.

1.2 Motivation

The rapid expansion of the field of data communication has attracted increased attention to the importance of frequent and timely data delivery. Whether a user is connected via wired or wireless means, the demand for prompt data transmission to the intended destination has become critical. This demand spans various types of users, including human beings communicating through digital channels and sensor networks composed of multiple sensors that need to intermittently send data to a designated source. In response to these evolving needs, researchers have introduced the concept of the Age of Information (AoI). AoI is a metric that quantifies the freshness of the data by measuring the time it has elapsed since the last update from a specific user or source till it reaches its destination. This concept is particularly relevant in multi-source or multi-user environments, where data from numerous sources converges at a single point, creating a need to manage and prioritize the flow of information effectively. In such complex scenarios, several critical concerns arise. For instance, ensuring that data from users with urgent needs is not delayed or stalled is paramount. At the same time, it is essential to optimize the use of limited network resources to avoid inefficiencies and wastage. Balancing these requirements requires innovative approaches and solutions.
To address these challenges, researchers are exploring a variety of strategies. An approach is the development of advanced scheduling algorithms designed to optimize the transmission of data from multiple sources, ensuring that all users are accommodated

in the most efficient manner possible. These algorithms must consider factors such as the urgency of the data, the availability of network resources, and the overall system load. In addition, the integration of machine learning techniques is being investigated as a means to minimize the average AoI. By leveraging machine learning, systems can dynamically adjust to changing conditions, predict potential bottlenecks, and optimize data flow in real-time. This can lead to significant improvements in the overall efficiency of data communication systems, ensuring that information remains fresh and relevant while minimizing delays.

In conclusion, the expanding field of data communication has underscored the importance of timely data delivery, particularly in environments where multiple sources are competing for limited network resources. The concept of AoI has emerged as a crucial metric to assess data freshness, driving the development of new technologies and methodologies to optimize data transmission. Through the creation of innovative scheduling algorithms and the application of machine learning, researchers are working to ensure that data delivery remains efficient, timely, and responsive to the needs of all users. Age of information confinement can be studied and applied under different scenarios. As we know, in each network there can be different types of scenarios. Hence in each network topology, the limiting age of information can have different needs. Some of the possible network topologies are discussed below.

1.2.1 Network Topology

Network topology or layout talks about the physical layout of a network. It tells how different devices of a network are connected and how the data flows between them. Network topologies have two main classifications; One is their physical layout or arrangement which tells how devices are connected on a hardware or physical level, whereas the second type is the logical topology, which tells how data will flow in the network regardless of the physical arrangement of the network components. Network topologies can be of several types, a few of which are discussed below.

1.2.1.1 Bus Topology

Bus topology is the simplest topology in which there exists only a single path for data to travel in a network. In addition, data can travel in only one direction. When some network element wants to send its data to some other network element then it uploads its data on that bus or wire. That data travels along the network wire or bus and reaches its destination while passing through each network element. Managing the age of information in this topology is just like solving a serial combination of network devices, and when we consider such serial setting, then its final result is simply a sum up of each individual's output. Thus, in order to find out the entire network's age of

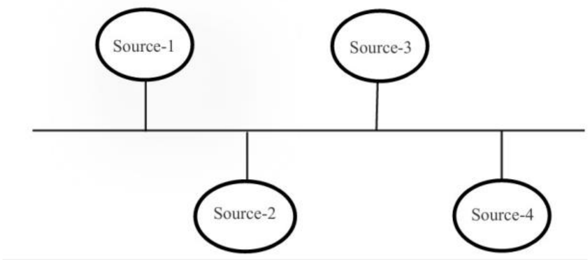

Figure 1.1: Bus Topology

information, we simply need to plug in the output of any hop to next hop's input and keep on summing up their output till the end of entire network's chain.

1.2.1.2 Star Topology

In start topology there is a central main hub at the output of each network source. Whenever some user sends its data to some other user, this data packet carrying its destination address goes to that central hub. after receiving data, hub decodes the address and chooses the desired path according to the address carried by the arriving data packet and then sends the packet to that specific source only. Hence in this topology data of each source only moves to its desired destination. But this topology is a bit costly and is comparatively difficult to implement. This hop is an example of a

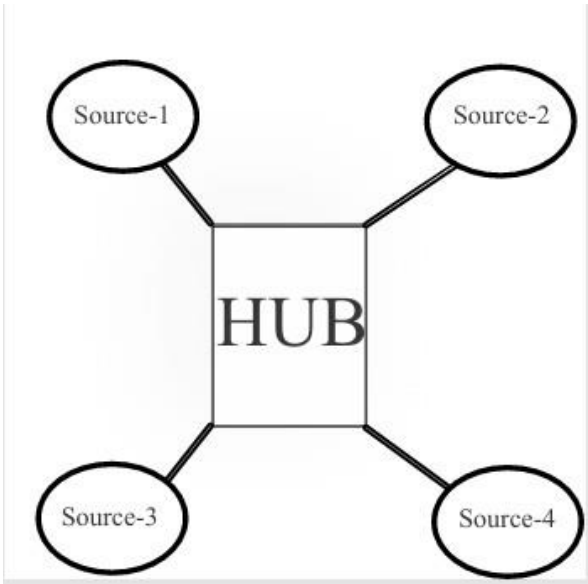

Figure 1.2: Star Topology

two hop networks. Here, sender acts as first hop and central hub or switch is working assecond hop. Meanwhile, the receiver is the desired destination for each sender. Thus, we can say that calculating the age of information in such a setting needs to consider a two-hop network, and their output relies on the collective impact of each of these two hops.

1.2.1.3 Mesh Topology

Mesh topology is another very famous network lout. In this topology, each network node has a dedicated path with each node. That is, if some ’x’ mode has 3 other nodes in its networks, then node ’x’ will have 3 paths to communicate separately with each other network node. This is the most efficient type of network topology. But as the network nodes increase its complexity also increases drastically, eventually increases its cost of implementation. As we have seen that there exists a direct path between each network element so this topology can be considered as a special case of age of information. Although it is difficult to implement topology, it can help to achieve minimum age of information, which is an ultimate goal of any communication network.

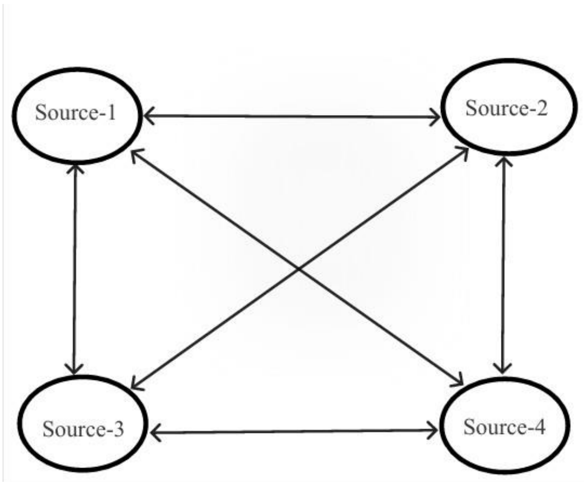

Figure 1.3: Mesh Topology

In addition to these topologies there can be number of other network topologies and each can have different behavior against age of information. Like in mesh topology,it seems that there will be a minimum age of information as there is a direct path between each network node. But in bus topology, the age of the information can vary depending on the position of nodes communicating with each other.

1.2.2 Network Type

After network topology, network type also matters alot while studying age of information. Type of network can vary depending on different parameters like architecture, functionality, geographic layout and type of data network is handling.

1.2.2.1 Point-to-Point

Point-to-point communication where two devices are directly linked and communicating with each other. In such a scenario, the age of the information can be studied easily as there is no chance of link congestion or data packet collision. Eventually, in point-to-point communication, the age of information depends on distance and protocol being used for communication.

As point-to-point communication does not involve any intermediate hop, we can say that it is a simplest type of communication. Hence, age of information in this case does not need any minimization technique.

1.2.2.2 Broadcast or multi-point

Broadcast or multi-point network refers to a scenario in which more than two devices are communicating with each other. In such a scenario, multiple concerns arise, and minimizing the age of information becomes a demanding task. Like when multiple devices are communicating with each other than collision probability increases rapidly. In addition, network congestion can also occur due to poor network management. Hence in such network data of any source can get stalled and may cause rise in age of information of some source.

Broadcast or multi-point communication involves multiple intermediate nodes or hops to complete a communication link. In such networks, scheduling age of information is a crucial and also a demanding task. At each network node, a different network response is expected. In addition, the number of users is also an unexpected event. Finally, in such cases random values for age of information are derived and on basis f these assumed values, such networks are configured.

1.2.3 Geographic Coverage

Another network type lies under coverage area of any network. Like local area network (LAN), wide area network (WAN), body area network (BAN), etc. These coverage area classifications tell us the range of any network's communication. When this coverage area increases age of information also increases. Like in local area network, which extends up to few meters only, no any network repeater or range extender is required and data packets directly reach their desired destination in minimum possible time.

Hence, the age of the information stays at the minimum level. Meanwhile, wide area network which extend between countries and continents, number of different transmission media like satellites or leased lines are used. In such networks, data from the source cross several nodes to reach its destination. In addition, multiple sources are often accommodated simultaneously in such network. Hence it may lead to multi user and multi hop setting. And in such scenarios, no any source's data should be trapped in some waiting queue. Hence age of information becomes of vital interest in such cases.

1.2.4 Functionality

The type of network functionality is also of prime interest. It deals with the accommodation of multiple users in a network. In single user scenario, managing network becomes easier as there is no any chance of data packet collision or congestion. But in a multi user network poor data handling can lead to system failure. In such cases different types of circuit switching concepts arise. These concepts are discussed in sections below.

1.2.4.1 Circuit Switching

In a circuit switched network, only a single user is allowed to send its data to some remote destination t a time. Hence no collision or such latency phenomena can occur, and finally the age of information remains at the minimum level. But when multiple users are communicating on the circuit switched network, all other users will have to wait for the first user to hang up. This can cause a drastic increase in the age of information for all other users.

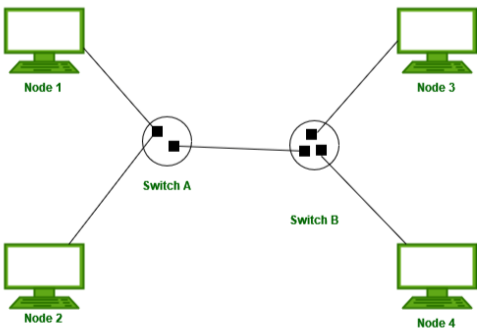

Figure 1.4: Circuit Switching

1.2.4.2 Packet Switching

In packet switched network, the data of all users is divided into packets and sent to a remote destination via a single communication channel. In such setting, data packet collision and packet lost probability increase directly with number of users. Hence, if a data packet of any user is lost, this can cause the age of information to rise, eventually degrading the entire network's performance.

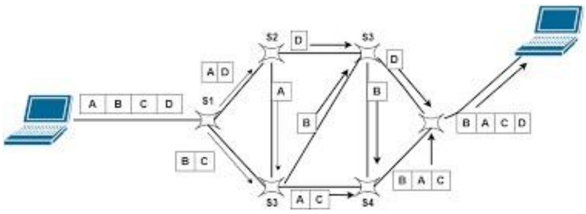

Figure 1.5: Packet Switching

1.2.5 Network Symmetry

Network symmetry also matters a lot in any network's functionality. Symmetry of any network can vary on basis of different parameters like consistency in the structure, capabilities, and behavior of the network's nodes and links etc. Basically, networks are divided into two parts on basis of concept of symmetry. These two types are given below.

1.2.5.1 Symmetric Network

In a symmetric network, minimizing the age of information is not a big deal. Like when the behavior of each node of some network is consistent then, it needs to be scheduled once and when minimum age of information is achieved, then that system is locked to that setting. Hence, upon each instant of such network implementation, all possible network behaviors are known and network can be implemented easily.

1.2.5.2 Non-Symmetric Network

When behavior of network keeps on changing like service rates introduced by each server vary on every iteration, or the number of available channels for transmitting data is inconsistent, or the time taken by each channel to transmit data to some specific destination keeps on changing, then this can lead to non-symmetric network behavior. This non-symmetric behavior requires the designer to schedule all sources every time before network implementation. Hence, we can say that the age of information minimization is a challenging task in non-symmetric network setting.

1.2.6 Scheduling in Networks

The word network refers to connection of two or more than two devices. And when multiple devices communicate with each other than scheduling of these sources becomes a demanding task. Number of different scheduling policies are being introduced by different researchers and each policy has got application in industry according to its estimated performance. Some scheduling policies are discussed below.

1.2.6.1 First Source First Serve

This scheduling policy bears a strong resemblance to the queue model, a common approach in various service systems where entities are attended to base on the order of their arrival. Unlike in a queue, the first person to arrive is the first to receive service, and this scheduling policy operates on a similar principle with data packets. Each packet is queued up, and the one that arrived first is given priority for service. The process is straightforward: once a data packet from a specific source is selected for service, it is processed, and the remaining packets wait their turn, following the same procedure in sequence.

A closely related scheduling approach is the First Come First Serve (FCFS) policy, which is widely recognized for its simplicity and fairness. In FCFS, the primary criterion for prioritizing data packets is their arrival time. As each data packet arrives at the service node, it is placed in a queue according to the exact time it was received. The packet with the earliest arrival time, the one that has been waiting the longest, is the first to be selected for service. This method ensures that every packet is processed in the exact order of its arrival, without other factors influencing the sequence. It is a straightforward, time-based approach that is easy to implement and understand.

However, there are key differences between the FCFS policy and other, more sophisticated scheduling strategies. Although FCFS is entirely dependent on the arrival time of each data packet, which means that the packet that arrives first is always prioritized, it may not always result in the most efficient system performance. For instance, FCFS does not consider the size of the data packet, the urgency of the information it contains, or the time sensitivity of the service required. This can lead to situations where smaller or less critical packets are delayed because they arrived after larger or more urgent ones. As a result, in scenarios where the freshness of data (as measured by the Age of Information, or AoI) is critical, FCFS might not be the optimal policy.

In contrast, more advanced scheduling policies incorporate additional factors beyond just arrival time. These can include the time a packet has already spent in the system, its service time, or even its importance relative to other packets. Such policies aim to optimize performance metrics like AoI by ensuring that the most critical packets are serviced in a timely manner, even if they did not arrive first. For example, a scheduling policy that uses timestamps not just for arrival but for partial service times can prioritize packets that have already been partially processed, ensuring that they reach the destination more quickly and keeping the information as current as possible.

1.2.6.2 Earliest Served First Serve

This scheduling policy is designed around the service time of each data packet, prioritizing packets based on the time they have already spent in service. When a packet from a specific source is processed, a timestamp is assigned to that source at the time of its replacement. Once this packet completes its service, the system retrieves the next packet from the buffer for service. The key aspect of this policy is the method by which the next data packet is selected for service. Rather than following a simple queue or random selection, the policy prioritizes packets based on the timestamps assigned during previous services. Sources that have already received service for some durations are given precedence over others, ensuring that their data packets are selected for delivery to the destination before packets from sources with less service time. This prioritizationmechanism is intended to reduce the overall Age of Information (AoI), as it ensures that sources with partially serviced packets are promptly attended to, thus maintaining more current information across the network. The mathematical representation of this policy is given in Eq. 3.16

1.2.6.3 Single Buffer with Replacement

This technique aims to optimize buffer utilization in network systems by introducing a method where each source has a fixed data storage capacity, allowing only one packet to be stored in the buffer at any given time. This policy is dependent on state of buffer hence state of buffer can be given as follow:

$$Q_{buffer}(t) = \begin{cases} 1 & \text{if a packet from source } I \text{ is in the buffer} \\ 0 & \text{if the buffer is empty} \end{cases} \tag{1.1}$$

Unlike traditional approaches that may rely on complex scheduling algorithms, this method is scheduling-free and focuses purely on efficient buffer management. When a new data packet arrives from a specific source, it replaces the packet currently residing in the buffer. This replacement strategy significantly reduces the need for large buffer spaces, enabling the system to accommodate a greater number of sources within a limited buffer size.

1.3 Research Gaps

IOT is a network of devices which are inter connected via some wire or wireless, to exchange some useful information between various devices. Number of researches have been carried out in figuring out importance of AOI but still there are number of parts which still seek attention of researchers. Wireless Sensor Network (WSN) usually involve usage of many network elements like routers, gateways, switches each performing its specific task. In addition to numerous devices, there can be number of different network structures or topology like some networks use simple wire for communication called bus topology, some use dedicated paths for inter connectivity of each node of network to every node of network known as star or mesh topology etc. In addition to these topology, mode of communication can also vary, like some networks use same network protocols for communication known as symmetric, and some work on different protocols known as non-symmetric networks. In addition to these there exist number of network concerns or variations which can cause different types of complications in ensuring smooth communication. One of major concern is to ensure that no data of any sensor should be stalled and this can be achieved by minimizing AOI.

Several different scheduling policies have been proposed to minimize AOI, but there is still a huge gap to achieving this goal. There are a number of scheduling policies that are practically implemented in the real world but are not being implemented to minimize AOI. On the other hand, if someone has considered these policies then type of network, or possible versatility of network is not being considered which also creates a gap between theoretical work and real time scenarios. Some authors have tried to consider both of these considerations i.e. type of network and scheduling policies but they have used single scheduling policy and derived their result or conclusion on basis of that limited or confined considerations.

1.4 Contributions

To fulfill the aforementioned research gaps and limitations, the following contributions are provided in this research.

1. A novel concept of assigning weights to all data packets is introduced. These weights are assigned to data packets depending on their arrival time.

2. A comprehensive comparative analysis of three different scheduling policies, i.e. First Come First Serve (FCFS), Earliest Served First Serve (ESFS), and Single Buffer with Replacement (SBR), is carried out. The study compared these policies for a multi-source multi-hop, non-symmetric network, offering valuable insights into their effectiveness in minimizing AoI.

3. Symmetric and non-Symmetric both network conditions are implemented and compared and impact of network symmetry on age of information is also studied

4. The research employs crucial performance indicators, including the Cumulative Distribution Function (CDF) of AoI, Sum of AoI, and Age Violation Probability,

to thoroughly evaluate the impact of various scheduling policies. These metrics provide a comprehensive quantitative analysis of how each policy influences the freshness of information received at the destination.

Chapter 2

Related Work

The first wireless network that bore any real resemblance to a modern wireless Sensor Network (WSN) is the Sound Surveillance System (SOSUS), developed by the US military in the 1950s to detect and track Soviet submarines. Later on, WSN alongwith the Internet of Things entirely evolved the industry. Such systems were composed of networks of numerous sensors, machines etc. which were communicating or doing some specific tasks without human involvement. WSN is considered to be a central part of IOT which got application in almost every part of life [16]. WSNs are becoming more and more commonplace due to their adaptability and capacity to function in a variety of settings. Environmental monitoring is a well-known application in which WSNs are used to collect information on several parameters such as temperature, humidity, and pollution levels. Decision-making procedures can be informed and environmental changes can be detected with the usage of the obtained data. WSNs are used in body area networks (BANs) in the healthcare industry to track vital signs and instantly identify medical issues. The potential of wearable sensor nodes to gather and send physiological data to a central system for continuous monitoring and early diagnosis of illnesses like heart disease is demonstrated [7]

The term Internet of Things was coined in 1999 by the computer scientist Kevin Ashton who used the concept of Radio Frequency Identification for tracking objects in a supply chain [24]. This term proved to be a game changer in the field of scientific inter connectivity. Later on, further studies proposed another term which is known as Age of information which has got a prominent importance in real-time applications like networked systems, Internet of Things etc. This metric is of extreme importance in categorizing the working efficiency of any system. A system with minimum AOI can be considered as a highly responsive system and vice versa.

[20] considered the example of a vehicular system which was using different sensors to monitor the speed, location and such parameters of an automobile to ensure the safety and such user requirements. This paper proposed average system information age to characterize the working of this system. And under this proposed metric it

gave an estimate of time after which data from each sensor should be gathered to stay vigilant about the vehicular systems security. They proposed an optimal point working as information age metric which was lying between maximum throughput and minimum delay. In 2012, Sanjit Kol et al. proposed a system which employed the concept of time average age metric to figure out the performance of any status update system. This paper derived general metric to calculate the age of information metric which could be applied to any type of system and used the concept of First Come First Serve (FCFS) scheduling algorithm and proposed an optimal time frame in which a source should generate its status update [21]. A system of random status updates whose information packets are gathered at a point and sent to some remote destination wireless was studied in [8] in which data packets containing status update of some random packets were sent to a destination and concept of time stamping was used to note down the status update of each node. Exponentially distributed service time was defined as the time taken to send a data packet to destination without anyloss or failure. In addition, status update age was also defined which tells the time since last successful update received at receiver end. This setting was considering that the source node has the capability to schedule the data packets on the basis of theirlast successful status update. [9] considers such communication networks where a ran- dom process is observed, and samples are made available to a source node at random times. These samples are sent to some remote destination as status update samplesand hence called as status updates. These status updates are sent to destination in queues and remaining r weighting update packets are stored in some buffer. If buffer space is already occupied then on basis of certain values some packets are discarded to accommodate the newly arriving packets. Channel characteristics like fading, con- gestion etc are also taken in account to cater the difference in travel time of different data packets through the channel. In 2018, a book was published with title "Age of Information: A New Concept, Metric, and Tool" which tried to differentiate between latency, communication delay and Age of information. According to this work latency and communication delay are terms specifically used for communication systems, mean- while Age of Information can be used in communication as well as other sensor-based networks like control systems, information systems etc. It treated AOI as a tool to figure out the performance of any system [22]. Purpose of scheduling schemes usage is to ensure collision free data transfer eventually leading to efficient data transfer along with minimum energy wastage [27]. This paper has used the concept of Time divi- sion multiple access and considers that each network node is equipped with some finite capacity battery and each node is activated upon acquiring enough energy for transmis- sion of its data packet, finally end results have shown that recharging the nodes results in lengthening of link scheduler. Multi-Hop setting is also an important aspect where data traverses from multiple network points in order to reach its desired destination. This setting considers single source destination pair and activates each network link depending on certain probabilities and characterize AoI as a convex function of link activation rates [25]. UAV's flight trajectory, energy, and service time allocations for packet transmissions is studied as an example in [2], where these parameters are used to study the average peak age-of-information for a source-destination pair. Virtual-queue based policy and age-based policy along with available each instant channel state are studied and depending on various results it is observed that virtual queue based policy is achieving optimal results than age based policy [26]. A general formula for Age of information is derived in [17] which is applicable to a wide range of sensor networks where number of sensors are communicating and scheduling of data packets is direly needed. Age of Information timeliness metric is derived and on basis of obtained results a general AOI threshold is derived in [29], which is applicable to a wide variety of systems. Average status age for status updating multi system is derived under two conditions i.e. Poisson arrivals and exponential service systems using last come first served and first come first serve settings respectively. Concept of Hop but restricted to single hop only, was introduced in [18] which was working in a wireless network setting where a number of sensors or nodes were sending data to some base station which was scheduling this data on basis of sometime threshold. In reference [14], the energy consumption and AoI of a single-source node device were examined, taking into account the possibility of transmission failures resulting from sub-optimal channel conditions from the source node to the receiver. The related closed-form formulas for average AoI and energy consumption were derived for a threshold-based re-transmission strategy in the system. These expressions can be used to determine the maximum number of re-transmission attempts and channel failure probabilities. The Truncated Automatic Repeat Request strategy was used by the authors of [15]. It involves terminal devices repeatedly sending the current status update until they exceed the maximum number of permitted transmission attempts or generate a new status update. Based on the AoI evolution process, closed-form expressions for average AoI, average peak AoI, and average energy consumption are obtained. The majority of the situations examined by the authors of [30] involved the need for many information sources to communicate information in order to complete status updates, which lowers the amount of AoI. It looked into the issue of packet scheduling for application-oriented scenarios with correlated numerous information sources based on the freshness of the information. Specifically, it formulates the application-oriented scheduling problem as an MDP problem and uses DRL to solve it. It also uses AoI to characterize how recent status updates are for applications. In order to mitigate the possible performance loss brought on by the cohabitation of millimeter-wave radar and communication, Liang et al. presented an implementation technique for an Integrated Sensing and Communication (ISAC) system for vehicle networks by extending NR-V2X Mode 2. The ISAC system makes sure that high-priority vehicles occupy spectrum resources preferentially by using semi- persistent scheduling (SPS) resource selection and dynamically adjusting each vehicle's radar scanning cycle and transmission power based on the speed and channel conges- tion status reported by neighboring vehicles. The ISAC system may more effectively coordinate the coexistence of radar and communication functions, enhancing the overall performance and security of vehicle networks. Simulation findings confirmed the efficacy of this technique in enhancing radar and communication performance [23].

To understand this setting or to explore the feasibility of such setting three scheduling policies were developed which were trying to maximize the throughput of said system by minimizing the age of information. These policies included a randomized policy, a Max Weight policy and a Whittle's Index policy respectively. On the basis of simulation results Max Weight policy was outperforming the other two policies hence considered as best performing scheme in this setting. When to pre-emption is also an important aspect which plays a vital role in minimizing AOI and this pre-emption is dependent on a certain threshold level, which when met causes a data packet to be replaced by newly arrived data packet[28].A wireless broadcasts network with a base station is studied in [19] where the base station is sending data to several mobile users through unreliable channels. In order to minimize AOI a randomized policy, a Max-Weight policy and a Whittle's Index policy are considered and their results are compared, as per results both the Max-Weight and Whittle's Index policies outperform the other scheduling policies in every configuration simulated, and achieve near optimal performance. Scheduling error prone data packets is studied in [6] under a constraint i.e. the average number of transmissions at source end. In this setting the source receives a signal ACK/NACK from source which tells whether the data has been successfully received at destination or not. To implement this automatic repeat request (ARQ) and Hybrid-ARQ protocols are considered by the author. In scenarios with unknown environments, an average-cost reinforcement learning algorithm is introduced, which simultaneously learns the system parameters and the transmission policy in real time. The efficacy of the proposed methods is demonstrated through numerical results. Internet of Things (IOT) which is getting application is almost every domain of life was discussed under the AOI metric in [3]. In this research, freshness sensitive IOT systems were discussed and later on the differences between AoI and other well-known performance metrics in the literature, such as throughput and delay were discussed. every process under this setting was given a weight which was presenting the importance of that process and then minimum average sum of AOI was obtained for different processes t destination node. Value Iteration Algorithm (VIA) or the Policy Iteration Algorithm (PIA) were used to formulate the markovian decision process. Another survey on age of information was carried out by Roy D. Yates and his team in 2021 which tried to summarize the recent contributions in the vast area of AOI.AOI aware scheduling is one of the modern most concept in this domain which is applied in wireless body area networks (WBANS) which are deployed for remote assessment of physical training, patient care, and health monitoring for the aged. To prolong the life of WBANS and efficiently respond to some emergency, two concepts which serve as main performance indicators are Age of Information and energy efficiency [31]. SongtaoYeng and his team proposed the concept of erasures in Energy Harvesting channels where at every successful reception of data packet status of AOI register was erased to zero. This erasure may often happen because of noisy channel between source and destination and to implement this concept two different setting i.e. with feedback and without feedback were studied [10]. In 2022, another research was done which considered multi-source scenario where data from multiple users was to be transmitted to some remote destination through some wireless channel. In such setting minimizing AOI becomes a demanding task and to achieve this goal three different scheduling policies named as First Come First Serve, Earliest Served First Serve and Singe Buffer with Replacement are proposed and results have shown that Earliest Served First Serve policy is outperforming the other two policies by generating minimum AOI [12]. Ambient Intelligence (AMI) is a concept which deals with usage of sensor network in computing systems to realize the concept of intelligent computing. This idea is dependent on a cluster of sensors which also need network resources intermittently. AOI is such networks is dependent on the packet arrivals at source and also on type of scheduling policy used. The impact of scheduling policy, stochastic modeling is studied along with NOMA which is one of the key protocol or features of 5G and 6G technology [1]. Multi-source system under non-symmetric network setting is studied in a cache update system with a remote server delivering time-varying contents of multiple Internet of Things (IoT) items is considered in [13] under different service times setting. New data packets arrive at source node according to some Poisson process, where server is ensuring that the freshest packet from each source is considered for service. Different scheduling policies are considered in this setting to assure the binary freshness across the sources. The water-filling-based scheduling (WFS) policy, along with its extension known as the extended WFS (E-WFS) policy, are designed with worst-case complexities that are quadratic and cubic, respectively, in relation to the number of items. These policies are derived using convex optimization techniques applied to a relaxed version of the original system. Timely delivery of status update is of extreme importance. In another setting data from two independent sources was sent to some remote channel using a single server, where a newly arriving data packet can replace the already existing data packet hence ensuring the concept of pre-emption. Explicit expressions for the Laplace-Stieltjes transform of the time average age of information, and of the peak age of information are found in this article [11]. Successful deployment of Proportional Fair (PF) scheduling helps in maximizing the sum of the logarithms of user throughput. PF helps in maintaining balance between fairness and throughput, for conventional data traffic. The scheduling problem for the down-link of a cellular wireless network with a transmitter sending age-sensitive status update packets from multiple information sources to users with the goal of keeping the information as fresh as possible for the users is studied in [4]. Concept of slotted Aloha protocol is used in [5] where the author has used a random-access relay network to transfer the data from some source to some remote destination. Collision of data is possible under this protocol hence may cause stalling of data packet. To cater for this collision two management policies i.e., source prioritization (SP) or relay prioritization (RP) policies are proposed by the author. Moreover, an analytical model i.e., probability mass functionis also being proposed in this research.

Chapter 3

System Model

In this system model, we consider a network comprising multiple sources or sensors, each generating and transmitting data packets to a common destination or sink. The key objective is to minimize the Age of Information (AoI), a metric that quantifies the freshness of the information available at the destination. In this proposed system, simple bus topology for network is considered which implies that there exists only one path or channel, for data to flow. In other words, all network parts are connected in series. i number of sources are sending data packets periodically to some remote destination or sink. Data packet generation or arrival is denoted by λ. These data packets are managed by a server which is generating service rates for each source. These service rates are denoted by μ. These data packet traverse through h number of hops to reach the destination. At the end, destination node processes these packets and update the age of information status of each source. To incorporate the concept of non-symmetric network, each hop's server is assigned with different service times. Meanwhile each data packet is given with a time stamp which is serving as weight and on basis of these time stamp or weight, concept of weighted average age of information is studied. The standard time stamp for each policy is given in Eq. 3.1.

$$\Delta_i(t) \triangleq t - S_i(t). \tag{3.1}$$

where Δ_i is representing the time difference, $S_{\{i\}}(t)$ is giving service status or time stamp of source i and t is representing current time. Primarily, only the first network setting known as the first hop is considered and discussed in detail and is shown in Fig. 3.1. i number of sources are connected to this hop and are sending data according to a poisson process. The arrival of the data packet is denoted by 'λ'. Data packets from each source are placed in an allocated buffer whose storage space is equal to number of sources i.e. i. At output of buffer server is placed which selects packet from buffer for transmission. This server generates service times for each source denoted by μ. After scheduling of these packets, server selects source whose data packet should be sent to

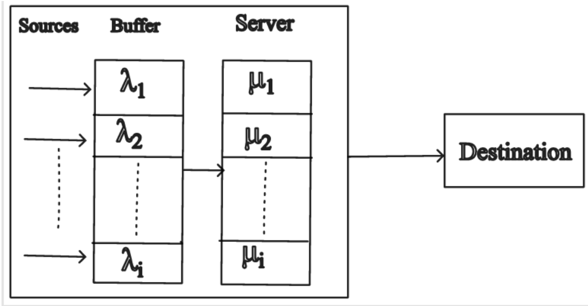

Figure 3.1: Single-Hop with single channel, i number of sources are sending data packets λ to some destination using a server producing service times μ

destination. As we are considering only a single channel, data will simply move to destination via that single channel to reach its destination.

To derive the age of information at first or any hop, primarily CDF, denoted by $F_i(x)$, needs to be derived for each source against each scheduling policy. It will serve as a guide to define the threshold levels. CDF can be calculated using Eq. 3.2, which in our case shows the probability that each source stays below a specific threshold value x.

$$F_i(x) = \sum_{h=1}^{H} F_{i,h}(x) \quad (3.2)$$

Here i is representing number of sources meanwhile h is representing the current hop's number. CDF values are helpful for two things. The first was to study the behavior of sources under different threshold levels and scheduling policies. Secondly, it can help to find the age violation probability of each source which can be calculated using Eq. 3.3.

$$ProbA_{violation} = 1 - F_i(x) \quad (3.3)$$

After calculating CDF, next step is to calculate age of information for each policy at output of server using Eq. 3.4.

$$AoI_{i,c,h} = f(\lambda_{i,c,h}, \mu_{i,c,h}) \quad (3.4)$$

This calculated Age of information can help to calculate various metrics of interest which can be helpful in understanding system's behavior in different environment cases.

After this, in the single-hop case, the output of the server is sent to the destination. But in multi-hop scenario this output is fed to upcoming hop's input where the same procedure is followed until the data reaches its destination. This setting is referred to as multi-hop system and is given in Fig. 3.2. Here we can see the output of first hop is fed to second hop where data from some other sources is also arriving. Then the same

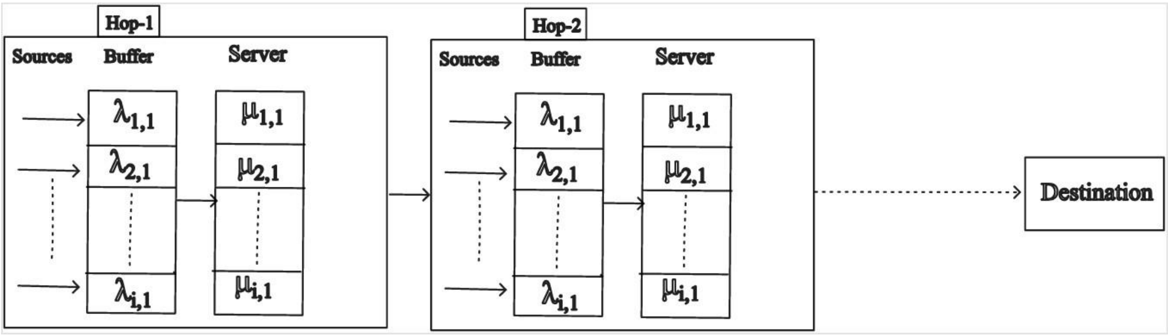

Figure 3.2: System Model for Multi-Hop where multiple hops are connected in a series and are sending data packets to a common destination

procedure of the first hop is repeated here and at all other remaining hops. As we are considering non-symmetric network, traffic arrival rates at buffer and service times introduced by server may vary from hop-to-hop and server-to-server and this difference is denoted as given in Eq. 3.5 and Eq. 3.6 respectively.

$$\lambda_{i,c,h} \quad \text{where} \quad \lambda_{i,c,h} \neq \lambda_{j,c,h}, \ \text{for } i \quad j \tag{3.5}$$

$$\mu_{i,c,h} \quad \text{where} \quad \mu_{i,c,h} \neq \mu_{j,c,h}, \ \text{for } i \neq j \tag{3.6}$$

Average age of information in this case is the expected value of age of information which is given in Eq. 3.7.

$$\bar{A}_{i,c,h} = \mathrm{E}\left[\mathrm{AoI}_{i,c,h}\right] \tag{3.7}$$

Finally at the end of entire procedure, total age of information is calculated using Eq. 3.8, which is a sum of the expected values of the age of the information across each hop.

$$\bar{A}_i = \sum_{h=1}^{H} \bar{A}_{i,h} \tag{3.8}$$

Average Age of information for non-symmetric network where more than one channels are considered can be calculated using Eq. 3.9.

$$\bar{A}_i = \sum_{h=1}^{H} \sum_{c=1}^{C_h} \mathrm{E}\left[\mathrm{AoI}_{i,c,h}\right] \tag{3.9}$$

Similarly, the overall CDF for single channel and multiple channels can also be calculated as given in Eq. 3.10 and 3.11 respectively.

$$F_i(x) = \sum_{h=1}^{H} F_{i,h}(x) \tag{3.10}$$

$$F_i(x) = \sum_{h=1}^{H} \sum_{c=1}^{C_h} F_{i,c,h}(x) \tag{3.11}$$

3.1 Scheduling Policies

As we have derived all possible formulas to calculate the age of information in multi-hop system. One missing thing is the scheduling policies. On what basis are these packets selected for service and sent to the server or destination. These aspects are dependent on scheduling policies. Numerous policies are in the literature, each having its own way of managing data. At server level, packets are selected based on a certain parameter. That parameter in our case is the value of age of information. As we have used three types of scheduling policies, the results of each of these policies are compared, and only a policy with minimum age of information will be selected for service throughout the channel. All of these policies, their way of work along with their mathematical derivations are discussed in upcoming sections.

3.1.1 First Source First Serve for Multi-Hop

FSFS policy is considered and, in this case, average age of information is measured using Eq. 3.12

$$\bar{\Delta}_{\mathrm{FSFS}_{i,h,c}} = \frac{\lambda_{i,h,c}}{2} E\left[X^2\right] + \frac{1}{\mu_{i,h,c}} \tag{3.12}$$

After substituting values for these parameters Eq. 3.12 becomes Eq. 3.13

$$\bar{\Delta}_{i,h,c} = \frac{1}{\lambda_{i,h,c}} + \frac{1}{\mu_{i,h,c}} \tag{3.13}$$

Here, *i* represents the source number, *h* is denoting the hop number, and *c* is showing the channel number, which in our case is equal to one as we are considering a single-channel system only.

$$\bar{\Delta}_1 = \frac{1}{\lambda_1} + \frac{1}{\mu} \tag{3.14}$$

Age of information for source-1 is given in Eq. 3.14 and Eq. 3.15 is used to measure the expected age of information for source-i when i>1.

$$\bar{\Delta}_{i,h} = \frac{1}{\lambda_{i,h}} + \frac{1}{\mu_{1,h}} + \frac{\lambda_{1,h}}{\mu(\mu - \lambda_{1,h})} \tag{3.15}$$

3.1.2 Earliest Served First Serve for Multi-Hop

General formula for this scheduling policy is given in Eq. 3.16 where the expected age of information for source *i* is calculated using inter arrival time and prioritization both.

Here T_i represents the time stamp for each data packet and $\frac{T_i}{\sum_{j=1}^{N} \lambda_j T_j}$ accounts for the prioritization effect, meanwhile $\frac{1}{\mu}$ represents the average service time for the source *i*.

$$\bar{\Delta}_i = E\left[\frac{1}{\lambda_i}\right] + E\left[\frac{T_i}{\sum_{j=1}^{N} \lambda_j T_j}\right] + \frac{1}{\mu} \tag{3.16}$$

Each source has a time stamp which is updated upon service completion and is given below where S_i is is presenting service time of source-i.

$$T_i \leftarrow T_i + S_i \tag{3.17}$$

According to MATLAB results, this scheduling policy demonstrates superior performance compared to other strategies, such as First-Come-First-Serve (FCFS) and Size-Based Routing (SBR). It achieves a lower average AoI, which is a critical metric in many applications where the freshness of information is paramount. The reduction in AoI suggests that this policy effectively balances the load and reduces the waiting time for packets, resulting in a more efficient and responsive network. This makes it an ideal choice in scenarios where maintaining up-to-date information is crucial, outperforming more traditional scheduling approaches.

3.1.3 Single Buffer with Replacement for Multi-Hop

Age of information in this policy is calculated using Eq. 3.19

$$\bar{\Delta}_{SBR} = E[X] + E[S] + E[X^2]/(2E[S]) \tag{3.18}$$

where

$$E[X] = \frac{1}{\lambda} \text{:The average time between arrivals.} \tag{3.19}$$

$$E[S] = \frac{1}{\mu} \text{:The average service time.} \tag{3.20}$$

$$E[X^2] = \frac{2}{\lambda^2} \text{:The second moment of the inter-arrival time} X. \tag{3.21}$$

Once a packet completes its service, the system immediately processes the packet that remains in the buffer, ensuring that there is no idle time and the buffer is continuously utilized. The simplicity of this technique lies in its ability to manage buffer space effectively without requiring intricate scheduling policies. By relying solely on the single packet stored in the buffer, the system can streamline operations, reduce latency, and efficiently manage network traffic. This method is particularly beneficial in scenarios with limited buffer capacity and a high volume of sources, as it minimizes the overhead associated with managing large buffer spaces and ensures that resources are used optimally.

Chapter 4

Results and Discussion

This chapter highlights the results of the entire dissertation. All simulations are done using MATLAB 2015a for a finite time duration varying from 1 to 'x' seconds where x can be any positive integer. We consider a non-symmetric system where data from multiple sources is injected to a network which is sending data to some remote destination using multiple hops and servers which are producing varying responses against each input. Whenever data from some single hop arrives at the succeeding hop, it gets mixed with data from some other sources, which are also sending data to the same destination.

In a multi-source, multi-hop, and multi-server network, each i-th source generates data packets denoted by λ. These packets pass through several intermediate servers, each of which may introduce varying amounts of delay represented by μ, known as service time, before the data can move on to the next hop on the network. The service time for each source at a given server is often modeled using different or identical distributions, referred to as s. The variability in service times between different servers and hops creates a complex dynamic in which AoI at destination is influenced by multiple factors, including the order in which packets are processed, the network topology, and the overall traffic load.

4.0.1 Results of Non-Symmetric Network

To evaluate and optimize the performance of these networks, several key metrics are analyzed. Primarily CDF for each source is calculated using each of the three policies, and their results are compared with single-hop results to validate the path followed to implement multi-hop system. Figures 4.1 and 4.2 show the CDF of each source for the FSFS scheduling policy respectively, where τ_o is representing age threshold. From these graphs, we can see that the graph follows the same trajectory in both of the single- and multi-hop scenarios. That is why we can say that for FSFS we have implemented the multi-hop system correctly.

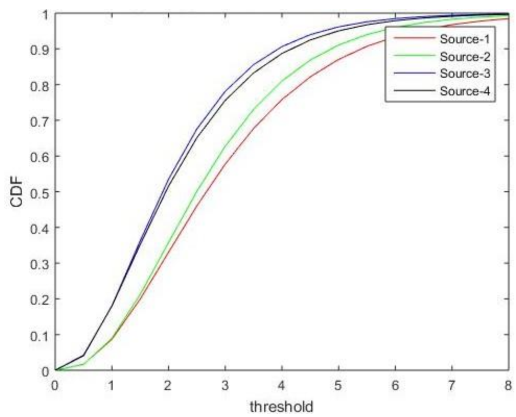

Figure 4.1: Single Hop's CDF for FSFS under unequal service rate scenario

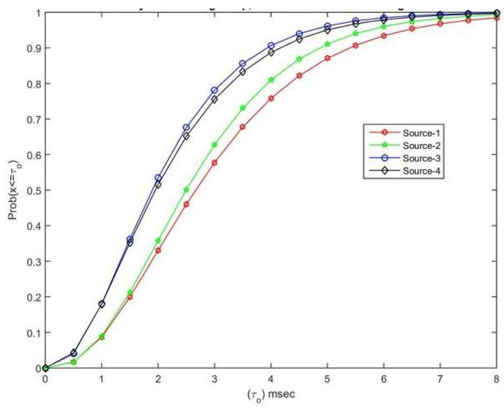

Figure 4.2: Multi-Hop's CDF for FSFS

In both figures, the curves exhibit a similar general shape, indicative of the performance of the FSFS policy across different network configurations. However, the precise behavior of the curves varies slightly between the single-hop and multi-hop scenarios. In single Hop the CDF curves for different sources are slightly more spread out, indicating a more pronounced difference in performance between the sources in the single-hop scenario. Meanwhile in multi-Hop figure the curves are closer to each other, suggesting that the performance difference between sources is reduced when considering a multi-hop network with varying service rates.

Hence, we can conclude that single-hop shows more pronounced differences between the sources, indicating that some sources perform better than others in a single-hop scenario. Although the multi-hop system indicates a reduction in performance differences between sources, likely due to the network's ability to adapt to varying service rates across multiple hops, thereby balancing the overall performance. Next figures are comparing the same CDF plots for ESFS policy with almost the same impact. Figure

4.3 is showing CDF for single hop under ESFS policy and Fig. 4.4 is plotting the same results but under multi-hop case.

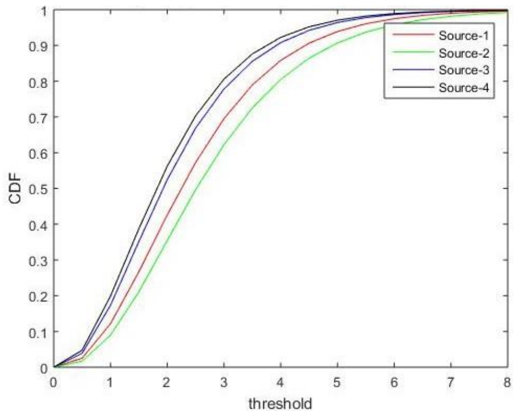

Figure 4.3: Single Hop's CDF for ESFS

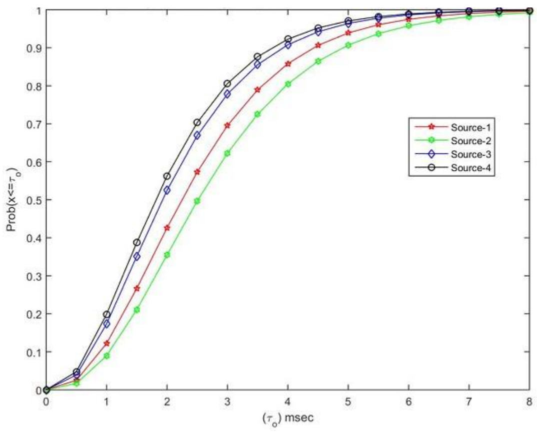

Figure 4.4: Multi-Hop's CDF for ESFS

The curve rise is same in both figures enough for validation of results. In single hops the curves are clearly spread out showing that there is a difference in performance of each source under the ESFS policy. In multihop case, curves have gone slightly closer, which indicates that the differences between sources are less pronounced when accounting for multiple hops and varying service rates. In single-hop case, source-4 shows the best performance over the other 3 sources by reaching higher CDF value more quickly, implying that under different service rates scenario, source-4 has a higher tendency to stay below a defined threshold value. Meanwhile in multi-hop case, closer curves show that different service rate eventually results in equalization of response of all sources. Below, Fig. 4.5 indicates response of each source in single-hop setting against third scheduling policy, i.e., single buffer with replacement, and Fig. 4.6 also represents the same but in multi-hop case. The similarity in the slopes shows compliance with the actual results. In the single-hop scenario, the CDF curves are more apart with source-

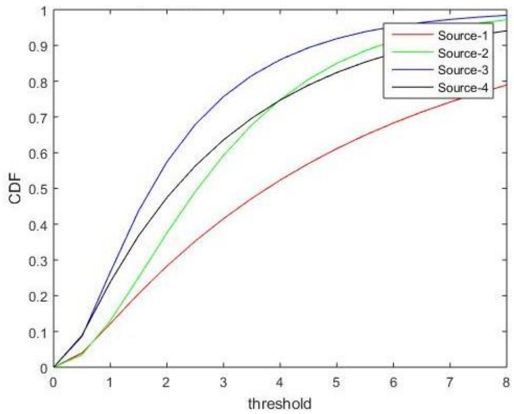

Figure 4.5: Single Hop's CDF for SBR

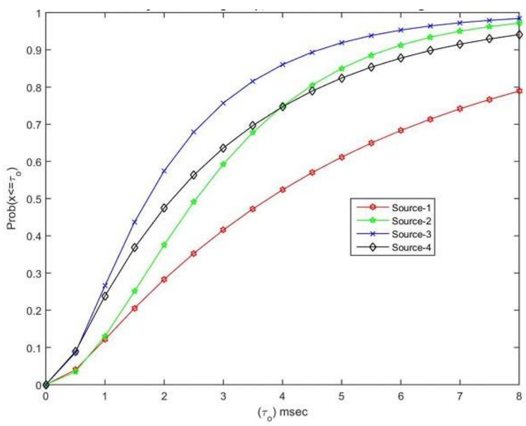

Figure 4.6: Multi-Hop's CDF for SBR

1's curve with slowest increase which shows that under given arrival rates, source-1 has least probability of exceeding the threshold value than other sources. Meanwhile in multi-hop case, curves of source-1, source-2 and source-3 are close together specially forthreshold values greater than 2. Source-4 gives higher values of CDF throughout all threshold values, thus showing that it will mostly remain under the threshold curve.

After CDF next step is to calculate age violation probability using Eq. 3.2. To calculate it, multiple values of age threshold are defined and system's response is observed and obtained results are given in Fig. 4.7 From this figure we can see that with the increase in threshold value, the probability of violating that threshold value decreases as low as 10^{-7}.

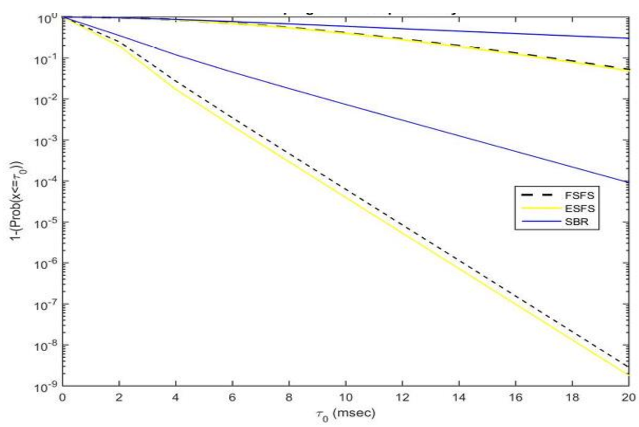

Figure 4.7: Multi-Hop age violation Probability

In this setting two values for system load are considered. This system load is a ratio of packet arrival rate for each source and service times given by the server to each source's packets. When the system load is given the value of 0.5, we can see that the probability of approaching age threshold increases with a great difference. ESFS and FSFS which are represented by green and red colors, respectively, are giving almost the same results and outperforming the third policy, i.e. SBR. Thus, in multi-hop setting and under low system load scenario both ESFS and FSFS mostly give same response.

When system load is increased to '4' then probability of violating the age threshold decreases drastically. In this case, all three policies are generating different results and are easily observable. In this case ESFS gives the best results by generating the minimum probability of violating the age of the information threshold. FSFS is between both of the ESFS and SBR which is giving intermediate probability with respect to the other two policies. SBR is proved to be a worse policy in this case, as its probability of violating the age threshold is higher than both other policies.

After age violation probability, the sum of age of information is calculated using the same system model. Primarily single hop's sum is calculated and, following the same procedure, multi hop's sum is calculated. Sum is calculated against the said system load for three different number of sources i.e. 2, 3 and 4. Lowest curves in graph are showing sum for two sources and highest curves are showing sum for four number of sources. Meanwhile, central curves are showing sum for three number of sources.

We can see that as system load increases from 0 to 2, the value of sum of age of information decreases rapidly, and from 2 to 10 this decrease becomes smooth. After reaching a specific system load response of age of information becomes almost linear. In addition, when number of sources is increased from 2 to 4, we can clearly observe an increase in sum of age of information for each case. This shows that when number of sources is increased, it will eventually give rise to sum of age of information and vice versa. Figure 4.8 shows the results of the sum of age of information in the multihop case. Red and blue curves are showing response of FSFS and SBR in first hop and

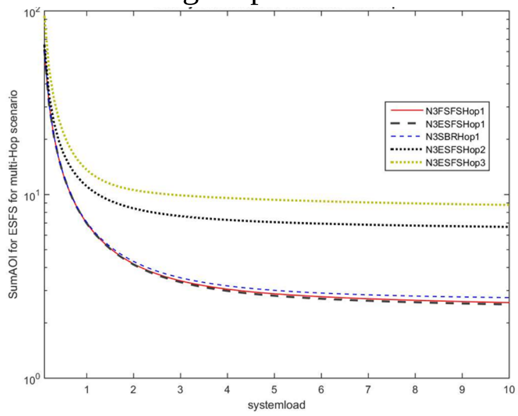

Figure 4.8: Sum AoI for multi-hop system vs different system load values

these both are giving bad response as compared to ESFS. Depending on these results only the ESFS response is plotted in next hops, which is showing almost the same behavior against system load variations. Just like in single hop's case, the value of sum of age of information also becomes linear after some values of threshold.

Another important aspect is that yellow and black curves show the results of ESFS in the second and third hops. As we have skipped calculation for FSFS and SBR in these hops, overall processing time has reduced, and hence sum of age of information has also reduced in these hops. Comparing these results shows that when a single scheduling policy is selected, it results in lesser computations, eventually reduces the complexity of entire system.

4.0.2 Results of Symmetric Network

These given graphs of CDF were under non-symmetric network setting, that is, the server was producing different service rates against each source's packets. But when the system was studied under a symmetric setting in which same service rates were introduced by the server, then a clear difference was observed in the graphs of CDF. Figure 4.9 shows the CDF of each source for the FSFS policy in a symmetric setting. From this figure we can see a clear overlapping of curves of different sources. This overlap indicates that, under symmetric network conditions, CDF of different sources often behaves in a symmetric manner. The same is the case with CDF of the same sources under the same system setting. Figures 4.10 and 4.11 show the CDF plots for each policy, respectively. Next is the plot of age violation probability under symmetric network setting. When this graph is compared with the same graph of non-symmetric

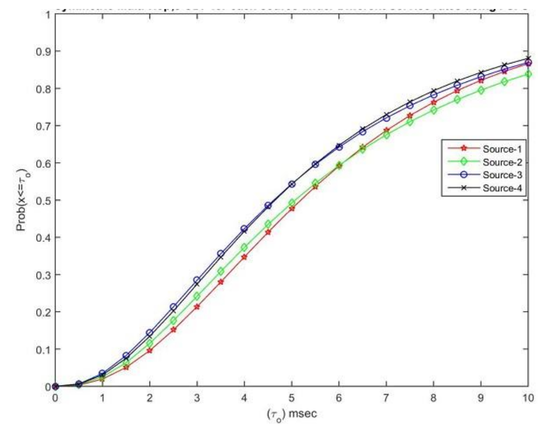

Figure 4.9: Symmetric Multi-Hop's CDF for each source using FSFS

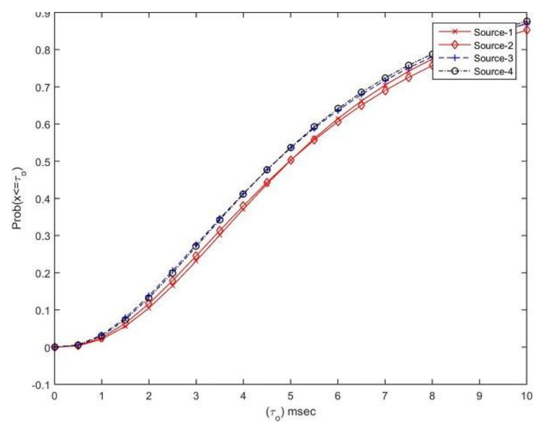

Figure 4.10: Symmetric Multi-Hop's CDF for each source using ESFS

case then we can say that in this plot value of age violation has decreased more than in non-symmetric graph. Hence, we can conclude that in symmetric network probability of age threshold violation can be decreased to a reasonable extent. Figure 4.13 is showing the sum of age of information in symmetric network. This graph's curve is also following the trajectory of non-symmetric graph. But here FSFS and ESFS curves have got closer indicating that in symmetric case where service rate are same, different policies often converge eventually result in overlapping of performance metric.

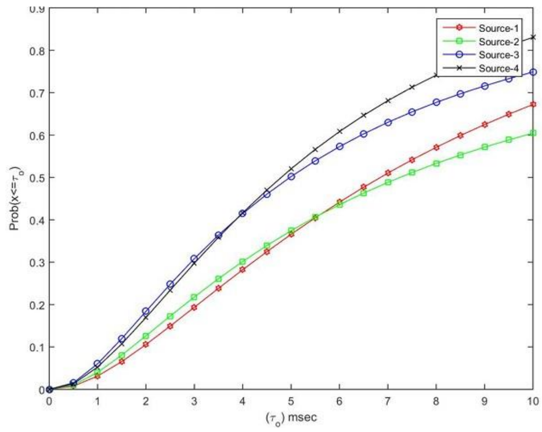

Figure 4.11: Symmetric Multi-Hop,s CDF for each source using SBR

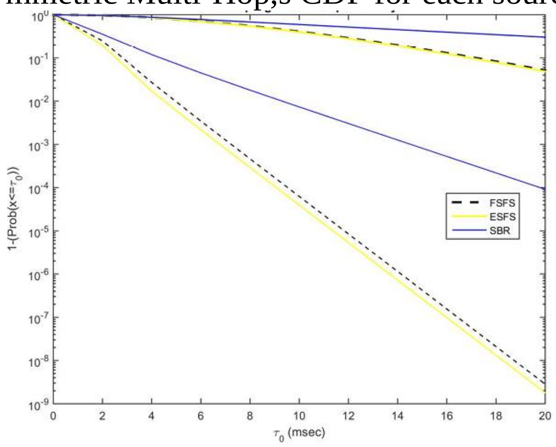

Figure 4.12: Symmetric Age Violation Probability

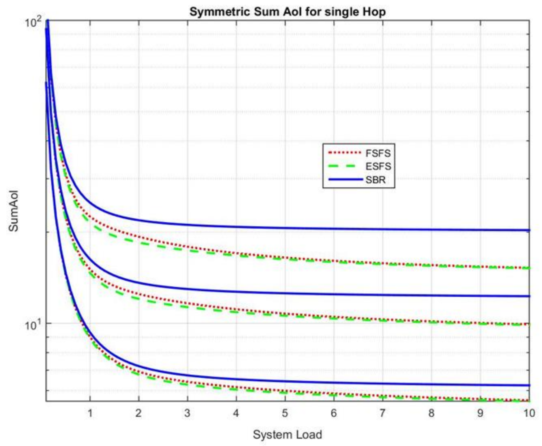

Figure 4.13: Symmetric Sum AoI

Chapter 5

CONCLUSION AND FUTURE RECOMMENDATIONS

One of the primary metrics of interest is the age violation probability, which measures the likelihood that the AoI of a data packet exceeds a predefined threshold. This metric is particularly important in applications where timely information is critical, such as in real-time monitoring systems, autonomous vehicles, or remote-control applications. High age violation probabilities indicate that the system frequently provides outdated information, which can lead to poor decision making or system failures.

The sum of age of the information is another field of interest, which is helping in measuring system response against different system load values. Using the results obtained, we can say that at very low system load values the response of the system varies a lot. Meanwhile when this threshold's value passes some specific value then this change becomes almost zero. So, we can say that under high system load inputs, system's response in either single hop or multihop systems becomes almost linear.

Another important metric is the average AoI, which provides an overall measure of the typical freshness of the information received at the destination. This metric is useful for assessing the general performance of the network and for comparing different network designs or communication strategies. A lower average AoI indicates that, on average, the data being received is more up-to-date, which is crucial for maintaining the accuracy and reliability of the system. Researchers often use the average AoI as a benchmark to compare the efficiency of new techniques against previously available methods.

There are a number of future aspects that can help minimize the age of information and are not being studied. In multi-Hop setting type of hop also matters and it we consider some relay as hop then there are different functions of each type of relay. Like Amplify and Forward relay which simply amplifies the received signal and transmits it to the next part of network. Such relays are used for range extension. Other types of relays include Decode and Forward and Compress and Forward. These relay types need to be considered, and their impact can be studied in the future and may offer some fruitful results.

As there exist number of network topologies but only serial communication or bus topology is studied. Hence future works can include considering other network topologies and study the behavior of network against these topologies.

This dissertation has considered only three types of scheduling policies, that is, First come first serve, Earliest Served first serve, and Single buffer with replacement. But there are number of other scheduling policies which can offer more efficient performance upon implementation. Researchers can add more types of scheduling policies and study their response.

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