

**T.C.  
ISTANBUL OKAN UNIVERSITY  
INSTITUTE OF GRADUATE SCIENCES**

**THESIS FOR THE DEGREE OF  
MASTER OF  
ADVANCED ELECTRONICS AND COMMUNICATION  
PROGRAM**

**Anmar Balasim KADHIM**

**SWARM ROUTING BASED ON  
ANT COLONY ALGORITHM IN NDNSIM**

**ADVISOR**

**Dr. Öğr. Üyesi Didem KIVANÇ TÜRELİ**

**ISTANBUL, January 2025**

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To My Beloved Family

Thank you for your support during my thesis.

With all my love and appreciation,

Anmar.



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# TABLE OF CONTENTS

ABBREVIATIONS .....	VIII
SYMBOLS .....	IX
LIST OF TABLES.....	X
LIST OF FIGURES .....	XI
ABSTRACT .....	XIII
ÖZET .....	XIV
CHAPTER 1. INTRODUCTION .....	1
1.1 PREFACE .....	1
1.2 OBJECTIVES .....	3
1.3 RESEARCH QUESTIONS .....	3
1.4 SCOPE .....	4
CHAPTER 2. LITERATURE REVIEW .....	5
2.1 NAMED DATA NETWORKING (NDN) .....	5
2.1.1 NDN System Services .....	9
2.1.2 Open Research Challenges .....	19
2.2 ANT COLONY .....	24
2.3 SWARM ROUTING.....	33
2.3.1 Properties of Swarm Intelligence.....	34
2.4 EMPIRICAL REVIEW .....	37

CHAPTER 3. RELATED WORK.....	42
3.1 MODEL PARAMETERS .....	44
3.1.1 Topology Configuration .....	44
3.1.2 Traffic Characteristics .....	45
3.1.3 Bandwidth of Links .....	45
3.1.4 Other Considerations .....	46
3.1.5 Type of Traffic.....	46
3.1.6 Simulation Environment.....	46
CHAPTER 4. SIMULATION PROGRAM .....	47
4.1 DESIGN .....	47
4.1.1 Architecture level.....	47
4.1.2 Application level.....	51
4.2 IMPLEMENTATION .....	54
4.2.1 Packet.....	55
4.2.2 Interface .....	55
4.2.3 Consumer .....	55
4.2.4 Producer .....	56
4.2.5 Node.....	56
4.2.6 Helper Modules .....	56
4.3 EXPERIMENTS .....	57
4.3.1 Scenario 1 .....	59
4.3.2 Scenario 2 .....	62
4.3.3 Scenario 3 .....	64
CHAPTER 5. RESULTS AND DISCUSSION.....	67
5.1 SCENARIO 1 .....	67
5.2 SCENARIO 2 .....	73
5.3 SCENARIO 3 .....	78
CHAPTER 6. SUMMARY AND CONCLUSIONS.....	82
6.1 INTRODUCTION .....	82
6.2 FINDINGS OF THE STUDY .....	82

6.2.1 Scenario 1: Validation of SI Implementation .....	83
6.2.2 Scenario 2: Pheromone Evolution .....	84
6.2.3 Scenario 3: Incorporation of Data Forwarding and Caching... ..	84
6.3 IMPLICATIONS .....	85
6.4 LIMITATIONS OF THE STUDY.....	86
REFERENCES .....	88



## **ABBREVIATIONS**

<b>SI</b>	: Swarm Intelligence
<b>ACO</b>	: Ant Colony Optimization
<b>RAM</b>	: Random Access Memory
<b>CPU</b>	: Central Processing Unit
<b>CS</b>	: Content Store
<b>PIT</b>	: Pending Interest Table
<b>FIB</b>	: Forwarding Information Base
<b>IP</b>	: Internet Protocol
<b>ICN</b>	: Information Centric Networking
<b>CN</b>	: Content Name
<b>ARQ</b>	: Automatic Repeat Request
<b>RTT</b>	: Round Trip delay Time
<b>PAT</b>	: Port Address Translation

## SYMBOLS

$p_k(r, s)$	Probability that ant $k$ will move to node $r$ when it is currently at node $s$ .
$T(r, s)$	The number in the routing table corresponding to the trail that has been established by prior ants
$E(r, s)$	Current congestion level of the link
$N$	The number of neighbors of the node $r$
$q_n$	Amount of artificial pheromone deposited on link $n$
$\alpha$	Heuristic adaptation parameter

## LIST OF TABLES

Table 4.1 Packet types. ....	49
Table 4.2 Variable descriptions. ....	57
Table 4.3 Variable values. ....	58
Table 4.4 Network and traffic variable values.....	58
Table 4.5 Summary of experiments.....	59
Table 4.6 Link Parameters for Scenario 1. ....	60
Table 4.7 Scenario 1: Ant behavior in the system. ....	61
Table 4.8 Link Parameters for Scenario 2. ....	63
Table 4.9 Scenario 2: Synergy between consumers. ....	63
Table 4.10 Link Parameters for Scenario 3. ....	65
Table 4.11 Scenario 3. Analysis of Data and in-network storage.....	65
Table 5.1 Content Store messages from Scenario 1. ....	77

## LIST OF FIGURES

Figure 2.1. Internet and NDN Hourglass Architectures [14].....	6
Figure 2.2. Timeline for NDN and other ICN [14], [17].....	7
Figure 2.3. Classification of Different Routing Schemes.....	10
Figure 2.4. Classification of Caching Strategies.....	11
Figure 2.5. Forwarding plane [42].....	12
Figure 2.6. Classification of Forwarding Techniques.....	12
Figure 2.7. An illustration of Delay-Tolerant Networking (DTN) and its interaction with connected networks [14].....	17
Figure 2.8. Data flow along the backward path of the IP packet [61].....	17
Figure 2.9. Classification of NDN Mobility Techniques.....	19
Figure 2.10. Ant Colony (AC) chooses between two bridges with different lengths $R_1$ and $R_2$ [68].....	25
Figure 2.11. ACO based routing.....	26
Figure 3.1. Methodology Flow.....	43
Figure 4.1. Routing packet flow of ant packets [100].....	53
Figure 4.2. Routing packet flow of content packets [100].....	54
Figure 4.3. Scenario 1: One consumer, one producer network topology.....	60
Figure 4.4. Two consumer network topology.....	62
Figure 4.5. Two producer network topology.....	64
Figure 5.1. Scenario 1. Simulation in ndnSIM visualizer.....	68
Figure 5.2. Scenario 1, Node 1 pheromone evolution in the faces for CBR traffic.....	68
Figure 5.3. Scenario 1. Node 2 to Node 4 pheromone evolution in the nodes for CBR traffic.....	69
Figure 5.4. Scenario 1. Node 5 pheromone evolution in the node for CBR traffic.....	69

Figure 5.5. Scenario 1. Packet delay for CBR traffic. ....	70
Figure 5.6. Scenario 1, Node 1 pheromone evolution in the faces for exponential traffic.....	71
Figure 5.7. Scenario 1. Node 2 to Node 4 pheromone evolution in the nodes for exponential traffic. ....	72
Figure 5.8. Scenario 1. Node 5 pheromone evolution in the node for exponential traffic. ....	72
Figure 5.9. Scenario 1. Packet delay for exponential traffic.....	72
Figure 5.10. Scenario 2. Simulation in ndnSIM visualizer.....	74
Figure 5.11. Scenario 2, Node 2 pheromone evolution in the faces for CBR traffic.	75
Figure 5.12. Scenario 2, Node 4 pheromone evolution in the faces for CBR traffic.	75
Figure 5.13. Scenario 3, Node 5 pheromone evolution in the faces for CBR traffic.	76
Figure 5.14. Scenario 2. Packet delay for CBR traffic (a) Customer 1 and (b) Customer 2. ....	76
Figure 5.15. Scenario 3. Simulation in ndnSIM visualizer.....	79
Figure 5.16. Scenario 3, Node 1 pheromone evolution in the faces for CBR traffic.	79
Figure 5.17. Scenario 3, Node 2, 3 and 4 pheromone evolution in the faces for CBR traffic.....	80
Figure 5.18. Scenario 3, Node 5 pheromone evolution in the faces for CBR traffic.	80
Figure 5.19. Scenario 3. Packet delay for CBR traffic (a) Producer (App) 1 and (b) Producer (App) 2. ....	81

# ABSTRACT

## SWARM ROUTING BASED ON ANT COLONY ALGORITHM IN NDNSIM

This study investigates the application of Swarm Intelligence (SI) in routing within Named Data Networking (NDN) environments. Through a series of experiments, SI-based routing algorithms are implemented, tested, and analyzed to evaluate their effectiveness, scalability, and adaptability. The experiments are focused on validating the implementation of SI, assessing its performance under various network conditions, and exploring its implications for routing efficiency. The findings reveal that SI-based routing demonstrates promising results in efficiently managing data delivery, dynamically adapting to changing network topologies, and optimizing resource utilization.

Additionally, the study identifies areas for future research, including optimization techniques, hybrid approaches, real-world deployment studies, security considerations, and application-specific evaluations. Overall, the study highlights the potential of SI-based routing as a viable alternative for enhancing routing efficiency and scalability in NDN environments. This work aims to be a step in paving the way for further advancements in networking technology.

**Keywords:** Swarm Intelligence, Named Data Networking, Routing, Optimization, Scalability, Adaptability, Real-World Deployment, Security, Hybrid Approaches, Application-Specific Studies.

# ÖZET

## NDNSİM'DE KARINCA KOLONİSİ ALGORİTMASINA DAYALI SÜRÜ YÖNLENDİRME

Bu çalışma, Adlandırılmış Veri Ağı (NDN) ortamlarında yönlendirmede Sürü Zekasının (SI) uygulanmasını araştırmaktadır. SI tabanlı yönlendirme algoritmaları uygulanır. Bir dizi deney aracılığıyla etkinliklerini, ölçeklenebilirliklerini ve uyarlanabilirliklerini değerlendirmek için test edilir ve analiz edilmiştir. Deneyler, SI'nın uygulanmasını doğrulamaya, çeşitli ağ koşulları altında performansını değerlendirmeye ve yönlendirme verimliliği üzerindeki etkilerini keşfetmeye odaklanmıştır. Bulgular, SI tabanlı yönlendirmenin, veri dağıtımını verimli bir şekilde yönetme, değişen ağ topolojilerine dinamik olarak uyum sağlama ve kaynak kullanımını optimize etme konusunda umut verici sonuçlar verdiğini ortaya koymaktadır.

Ek olarak çalışma, optimizasyon teknikleri, hibrit yaklaşımlar, gerçek dünyadaki dağıtım çalışmaları, güvenlik hususları ve uygulamaya özel değerlendirmeler dahil olmak üzere gelecekteki araştırmalar için yeni alanları tanımlamaktadır. Genel olarak çalışma, NDN ortamlarında yönlendirme verimliliğini ve ölçeklenebilirliğini artırmak için SI tabanlı yönlendirmenin uygun bir alternatif olacağını vurgulamaktadır. Bu çalışmanın, ağ teknolojisinde daha ileri gelişmelerin önünü açmada bir adım olması hedeflenmiştir.

**Anahtar Kelimeler:** Sürü Zekası, Adlandırılmış Veri Ağı, Yönlendirme, Optimizasyon, Ölçeklenebilirlik, Uyarlanabilirlik, Gerçek Dünyada Dağıtım, Güvenlik, Hibrit Yaklaşımlar, Uygulamaya Özel Çalışmalar.



# CHAPTER 1. INTRODUCTION

## 1.1 Preface

Named Data Networking (NDN) is a revolutionary network architecture that changes the meaning of basic network services from just delivering packets to a certain address to retrieving data with a given name. Interest packets are sent by data consumers, which include the names of the sought data. Any node inside the network has the potential to respond by sending Data packets that also include the same names. The recipient initiates an NDN conversation. Even if these packets of Interest-Data are moving in opposite directions, they nonetheless follow the same path across the network. In NDN, the unique feature of adaptive forwarding is made feasible by the symmetry of Interest-Data exchange and forwarding state information inside the network itself [1], [2].

To be more explicit, a node anticipates receiving a Data packet from the same interface it passed the Interest from within an acceptable amount of time (e.g., round-trip time), failing which it should get a NACK message [2] or timeout. Every node in this network contributes to the flow of information. The absence of a fixed infrastructure and the free mobility of the nodes in a NDN pose several types of challenges. One challenge is routing. Data packets are routed from their origin to their destination through a predetermined path in a network. The issue of swarm routing in NDNSIM is the primary topic of this study.

The Swarm Intelligence [3] paradigm is a computational framework that takes its inspiration from the cooperative character of biological systems like ants, rivers,

termites, and so on. Using a swarm of particles, this method seeks optimal solutions to the issue at hand. One of the many areas where swarm intelligence has proven useful is in the realm of network routing. Alternatives to conventional routing methods are needed, and swarm-based routing offers some promise in this regard. Because it employs software agents that can move about autonomously and adapt to new environments as they go, this method of managing networks is considered to be very flexible and efficient. Swarm Intelligence algorithms have been used on NDN before. In contrast, the idea of using the ANT colony algorithm for the routing is entirely new.

This group of optimization methods is called Ant Colony Optimization (ACO) and is modelled after the efficient and cooperative behavior of ant colonies. Ants are low-intelligence animals of nature that roam about their nests looking for food. The ant colony optimization mathematical method can be used to model ideas like finding food, building nets, dividing up work, mutual support, self-assembly, and setting up a graveyard. [4].

The term "swarm intelligence" (SI) is used to describe a specific kind of AI that is based on biological inspiration for its computing (AI). Gerardo Beni and Jing Wang initially used the term in 1989 [5], while they were working on cellular robotic systems, and it has since been recognized as a promising new topic. The increasing acceptance of SI-based algorithms may be attributed to a number of factors, the most prominent of which being the algorithms' adaptability and adaptability. Key traits demonstrated by the algorithms that have gained tremendous attention and identified various application areas are their self-learning capacity and tolerance to environmental fluctuations.

In recent years, swarm intelligence has gained traction as a solution to NP-hard issues, for which finding a global optimum in a practical time frame has proven very difficult. Solutions to such issues may theoretically have an endless number of permutations. When time is of the essence, it is crucial to discover a solution that will work. In practice, SI is useful for addressing nonlinear design issues in fields as diverse as data mining, optimization, artificial intelligence, business planning, bioinformatics, and manufacturing.

Swarm intelligence is inspired by the way in which some animal species are able to solve complex issues via coordinated group effort. It is premised on the idea that

individuals in a group can't handle complicated problems alone, but may be able to with some help from their friends. Algorithms that address and/or improve the routing problem in telecommunication networks have been designed using this idea. This kind of algorithm has been developed using models taken from animals like ants and bees [6]. Swarm intelligence algorithms are the outcome of several investigations and research efforts. These algorithms are inspired by ant behavior and work off of the central concept of making use of a chemical molecule called a pheromone. Foraging ants use this quality to build a highway from their nest to a food source. The foundation of each of these programs is the idea that after you've located the resource you need, you should leave a trail [7].

The Ants as a Management Tool This strategy is designed to function in symmetric networks that use load balancing. Using noise, delay, and ageing, it helps to prevent or at least mitigate complacency [8]. Heusse et al. [9] detail how forwarding ants may update their route knowledge without assuming that all paths have the same cost. The control of navigation, interferometry, the sensing of planetary motion, the management of microrobots, the identification and management of malignant tumours, and image processing technologies are all examples of high-end application fields. Due to the fact that swarm intelligence is still a relatively new area of study, there are not a great number of papers that deal with the subject. The exception to this is a select handful of the more prevalent methods, which have, once again, been overused. As a result, the authors' goal is to give a review in the field of Named Data Networking that analyzes swarm intelligence based on ANT colony algorithms (NDN).

## **1.2 Objectives**

The objective of this research is to devise, implement, test, and verify a Swarm Intelligence based Ant Colony algorithm for efficient routing in NDN.

## **1.3 Research Questions**

The purpose of this study is to answer the following

1. Is it possible for Swarm Intelligence to become a viable alternative to the existing routing techniques in Named Data Networking (NDN)?
  - What is a powerful architecture that successfully incorporates SI into a Named Data Networking (NDN)?
  - How exactly may the Named Data Networking (NDN) be modified to accommodate SI integration?
2. How Swarm Intelligence over NDN handle routing efficiency and scalability?
  - When the network topology expands, how does the system adapt?
  - When compared to other methods with a comparable goal, how scalable is SI?

## **1.4 Scope**

The objective is to get evidence that a SI method has the potential to become an alternative. Consequently, the results of the basic routing will indicate that the approach has promising behavior; nonetheless, they will not present a solution that is ready to be implemented. In addition, with respect to the scalability of the plan, the primary attention is being placed on determining the appropriate functioning of the components that may be affected by an increase in the size of the network.

## CHAPTER 2. LITERATURE REVIEW

### 2.1 Named Data Networking (NDN)

A brand-new Internet architecture is the Named Data Networking (NDN) protocol. The Internet still has an hourglass form, but the tight waist has changed. NDN receives data by name rather than sending it to certain places. On the one hand, this little change gives NDN networks the ability to employ essentially all of the Internet's tried-and-true technological capabilities to handle issues with digital distribution and management as well as IP communication obstacles [2], [10]. A distribution design, however, poses a number of new research challenges since it fundamentally departs from the point-to-point communication architecture that now governs the Internet. Simulators may be used to investigate and evaluate a number of novel design features. ndnSIM, an open-source NS-3-based simulator provides the larger research community with a common simulation platform that accurately duplicates the key elements of an NDN network in a modular fashion [11].

The architecture of ndnSIM follows the NS-3 network simulation principle of maximum abstraction for all displayed components. Similar to how the current IPv4 and IPv6 stacks may be implemented on simulated network nodes, ndnSIM is designed to be an independent protocol stack. Along with the fundamental protocol stack, ndnSIM also comes with a variety of easy to-use traffic generators, convenience classes (such as one to install the NDN stack and applications on nodes), measurement tools, and simulation statistics [12].

The Internet serves as inspiration for the fundamental architectural underpinnings of the NDN. The Domain Name System (DNS) and inter-domain routing policies are two of the key IP services that NDN is able to utilize directly. IP routing protocols, such as BGP and OSPF, may be readily transferred to NDN with just minimal modifications needed to be implemented. On the other hand, the NDN offers a number of improved features, which will be discussed in greater detail below. It replaces source and destination addresses with data packets that include names for the contents of the packets [13]. When compared to IP routers, routers that make use of distinct content names for communication are able to monitor the conditions of individual packets, which enables them to provide a greater variety of services. The data packets may be read and resent without regard to their original location. These capabilities facilitate user mobility and in-network caching of material for the purpose of satisfying future requests. In contrast to IP, NDN requires the producer of each data packet to sign it, and the consumer to verify the authenticity of the signature. Multi-path forwarding is a feature of NDN routers that allows a user's request to be sent to numerous interfaces simultaneously.

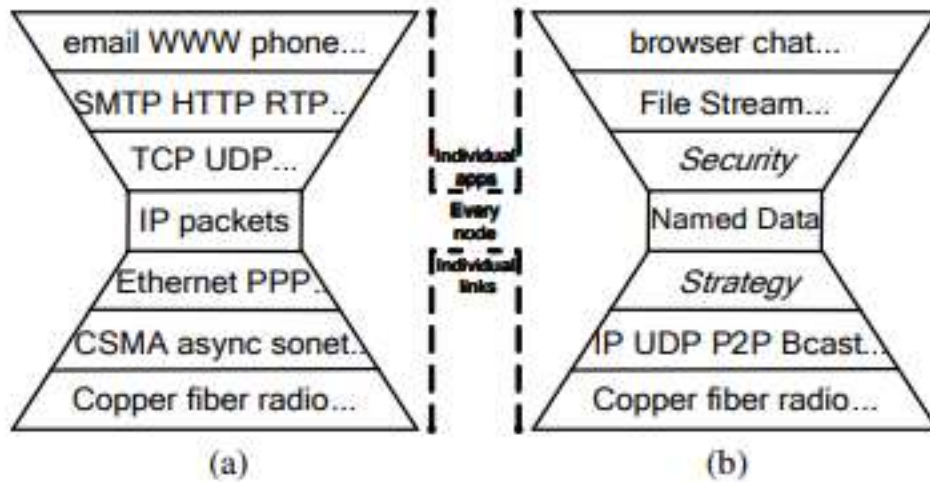


Figure 2.1. Internet and NDN Hourglass Architectures [14].

In addition, the need for application-specific middleware may be eliminated when content names are used for communication instead of those terms. Both the NDN and the Internet have a layered hourglass design, although there are certain functional variations between the layers of their respective hourglasses [15], [16]. This can be seen in Figure 2.1 (a) and (b), respectively. The sole protocol included at the Network

layer of the OSI communication paradigm is Internet Protocol (IP). However, it is difficult to add new functionality to the IP and much more difficult to alter the features that are already there.

The elimination of application-specific middleware is another benefit of communicating using content names. As can be seen in Figure 2.1 (a) and (b), NDN and the Internet both use a tiered hourglass design, although the respective levels serve different purposes [14], [15]. Only Internet Protocol (IP) is included at the Network layer of the OSI communication architecture. New features and changes to existing IP are challenging, though. The network layer of an NDN [15], [16] must provide scalability, security, resiliency, and efficiency if it is to serve as a future paradigm for the Internet.

Both security and strategy are new levels that have been introduced to the NDN protocol stack, as can be seen in Figure 2.1 (b). In contrast to safeguarding the whole of the communication route via the internet, the security layer protects each and every individual piece of material. The state-full NDN forwarding plane employs a strategy layer to determine the best path to take for each incoming content request. With NDN, there is no separate transport layer. The NDN forwarding plane incorporates all of the features and capabilities of the Internet's transport layer.

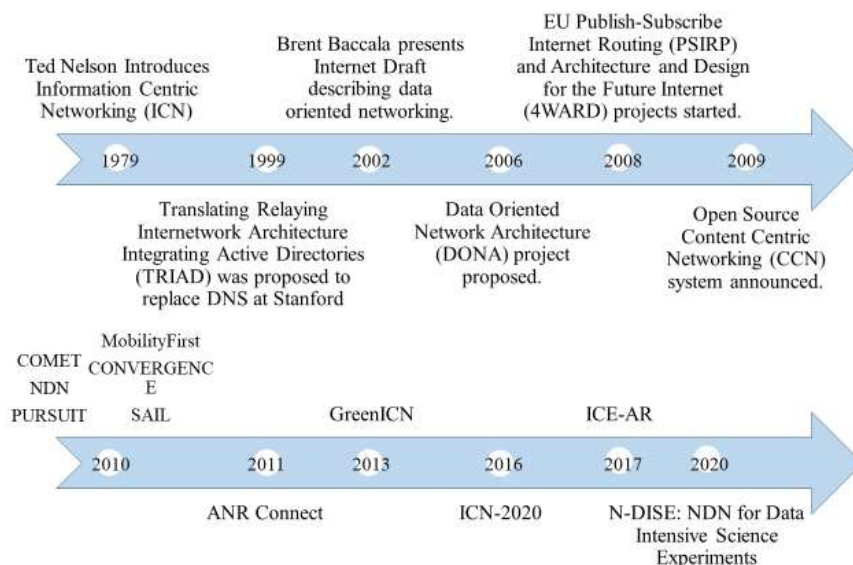


Figure 2.2. Timeline for NDN and other ICN [14], [17].

As can be seen in Figure 2.2, NDN developed out of the Information Centric Networking (ICN) field of study. As the changing nature of internet traffic became apparent to researchers, there were of plethora of research projects funded to establish a better architecture for the future internet [17]. Along with NDN, several alternative designs were introduced for information centered networking and a future internet architecture in projects funded by the US, EU and Japan such as FIND, NEBULA, XIA, GENI, 4WARD, FIRE, AKARI, JGN2Plus. These research into information centered networks and the efforts towards standardization are summarized by Keeping [18].

Since these projects started the internet and its use has changed dramatically. Internet access is now increasingly through mobile networks, on telephones. Starting with 4G LTE mobile networks using all-IP based routing in their infrastructure networks, since communication in general makes up only 4% of mobile and 2% of fixed traffic across the telecommunication network [19]. In addition, video streaming and social media together account for over 60% of internet traffic on both fixed and mobile networks, with the majority of traffic going to the top ten of media and social networking platforms. Many streaming media providers and social networks use the service of Content Delivery Networks (CDN) to deliver their information to the user. Others, like Netflix, house their own CDN. CDNs have massive international networks embedded within the internet at various locations. Since these companies focus on providing media services, they essentially run information content delivery networks as a separate layer on top of the TCP/IP network [20]. This situation reflects the early days of the internet, when the TCP/IP network would run across the telecommunication providers' circuit switched SS7 networks [15]. The current situation exists mainly through concerns firstly about whether the security and privacy of data can be preserved when NDN is used [21], [22] Research in this field is ongoing for both CDNs and other networks which may benefit from NDN [23]. Secondly there is the difficulty of changing the infrastructure of the internet as a whole. Standardization of ICNs is an ongoing process [18].

In addition to CDNs, the use of NDN has been explored for other 5G applications [24]. Internet of things (IoT) networks, which are often application specific and aim to jointly sense and transmit specific information. This is a natural fit for the NDN

framework [25]. NDN may also be useful in mobile networks of UAVs and vehicles, where the IP address is less relevant as the location of each node in the network changes continuously and quickly [25], [26]

While NDN is an exciting new technology with a lot of potential, it still has many unanswered research questions [27]. For example, there is no standard for identifying either the applications or the networks themselves, and there is no way to scale routing. There has been much interest in NDN as the future method for internet access, and work on developing better algorithms for naming [28] forwarding [29] routing [30] caching [31] and security [32]. While significant progress has been made on NDN in a very short amount of time, there has been no comprehensive assessment conducted to date that examines the architecture and characteristics of NDN.

## **2.1.1 NDN System Services**

What follows is a comprehensive overview of the most noteworthy approaches to NDN mobility, caching, forwarding, security, privacy, and trust that have been suggested recently.

### **2.1.1.1 Routing**

Routing is used in NDN to determine the network topology and rules, manage the network's long-term evolution, and refresh the forwarding table. The interface ranking and probing operations of the NDN routing protocol are coordinated with the NDN forwarding plane [33], [2]. Forwarding in NDN is identical to routing in every other respect; the only difference is that routing determines which routes are really available, whereas forwarding prioritizes and uses routes depending on their actual performance and status. With few tweaks, the link-state and distance-vector routing algorithm [34] designed for the Internet may be used to the NDN. The Forwarding Information Base (FIB) is used for the storage of routing-related data by both IP and NDN. When sending data, IP first looks for the target address in the forwarding information database (FIB) to identify the next hop; this may or may not be the most efficient path. To find the next hop, NDN consults the Forwarding Information Base (FIB); however, the retrieved data may not be the most local version. Modifications to the message

types (interest and data packets) and the addition of multi-path forwarding are all that are required to make the existing routing protocols of the Internet usable in NDN.

It is possible that the NDN routing table will use more RAM than the IP routing table because of the CNs it handles. CPU count, PIT count, memory usage, network utilization, Interest re-transmission rate, time to completion, etc. are some of the primary performance indicators used to assess NDN routing techniques [33]. As can be seen in , many different types of routing algorithms have been proposed for NDN routing. The primary routing protocols in NDN are: INFORM [35], OSPFN [36], NLSR [37] and DCR [38]. Many new algorithms have been proposed in recent years [30]. The role of the NDN routing algorithm and its interaction with NDN forwarding is also of interest [39].

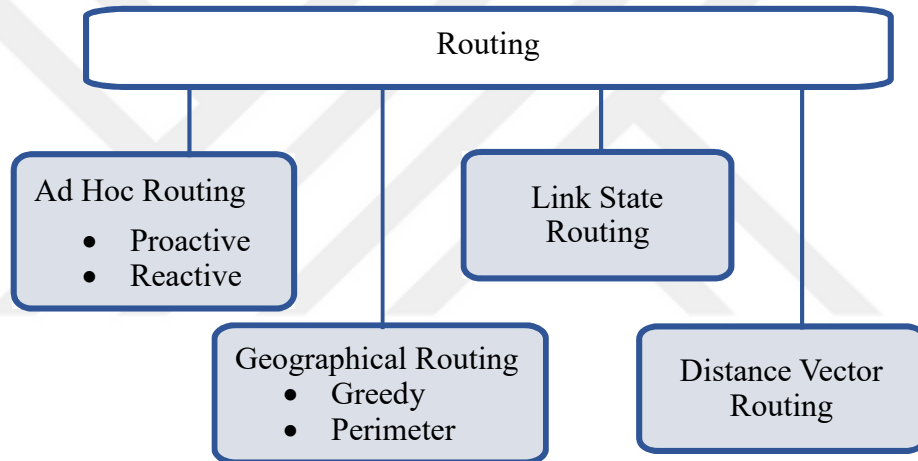


Figure 2.3. Classification of Different Routing Schemes.

### 2.1.1.2 Caching

It is vitally necessary to sustain the core notion of a content-centric, peer-to-peer data distribution model of NDN at a low cost, and content caching [31] at intermediate nodes is an alternative name for in-network storage. Caching in NDN offers a number of useful advantages. Caching the material that is created by other nodes helps to disassociate the content from the nodes that produced it. By making accessible several copies of the same material across the network, it not only lessens the workload on the producer's end but also eliminates the possibility of a single point of failure. It offers significant advantages to dynamic contents in the event of multicasting or

retransmission as a result of packet loss [34], [40]. In addition to this, it decreases the burden on the network as well as the delay in the data dissemination [16], [34].

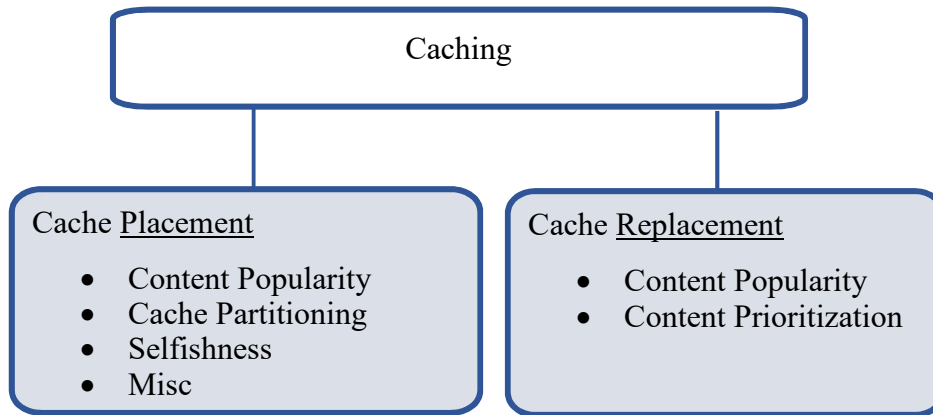


Figure 2.4. Classification of Caching Strategies.

The hit ratio, the content retrieval latency, the average number of hops traveled, and the total amount of time that elapses from the moment a content request is issued and the moment it is received by the consumer are the four metrics that are often included in the evaluation of the performance of a cache. Dissemination speed is another relevant cache performance indicator that evaluates the amount of time needed to distribute data all the way down to the network edge. It is up to the cache determination policy to decide whether or not the data packet should be cached in the intermediate routers. Two of the most crucial issues that need to be answered for a caching algorithm to be effective are: where in the network the content should be cached and how to prioritize which material to replace first. As a result, caching strategies can be described using two main factors: cache placement, which refers to the choice about where to store the material on the network, and cache replacement, which refers to the decision regarding whether or not to save the content on the router (see Figure 2.4).

### 2.1.1.3 Forwarding

The NDN routing plane is more scalable and reliable because its method of information transfer is based on the data rather than on IP numbers. It is possible for the forwarding plane to self-recover, which means that it is able to identify failures (node, link, or packet) and carry out recoveries such that there is no need for continual FIB updates [16]. In recent years many forwarding algorithms have been proposed

[41]. NDN forwarding can use many different strategies: adaptive forwarding, blind forwarding, energy efficient forwarding, congestion aware forwarding, next hop aware forwarding, neighbor aware forwarding, geo aware forwarding, provider aware forwarding [41]. Intelligent and stateful forwarding are supported by the scalability of the protocol. This allows NDN routers to monitor parameters such as round-trip time, throughput, packet loss, and alternate routing during periods of congestion and overhead. Due to the fact that NDN's forwarding strategies make all the decisions required for the interest packet and data packet forwarding, the forwarding plane also serves as a control plane.

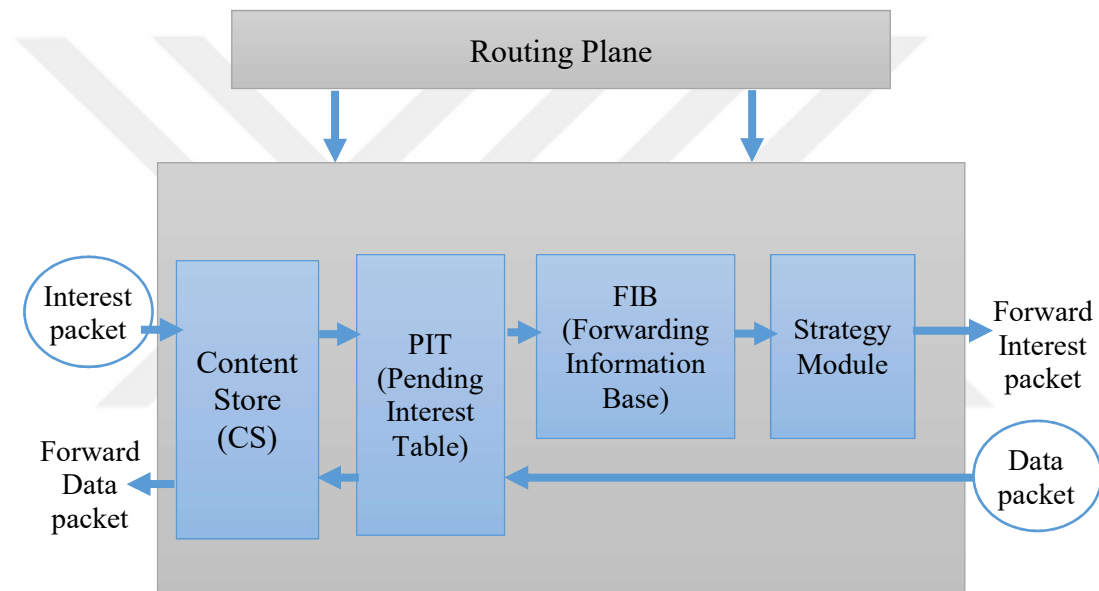


Figure 2.5. Forwarding plane [42].

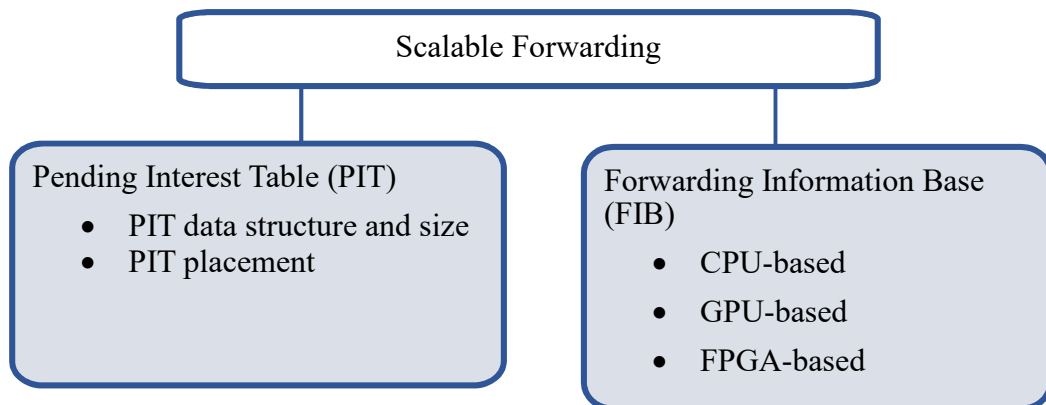


Figure 2.6. Classification of Forwarding Techniques.

#### **2.1.1.4 Security, Privacy and Trust**

One of the most fundamental necessities of any data-centric networking is content security [14]. In order to keep NDNs safe, you need efficient and low-cost security operations, trustworthy data management, and strong privacy safeguards.

##### **2.1.1.4.1 Security**

Every data packet in NDN is digitally signed using a standard public key, making it possible for any user to validate the data's genuineness [15]. Integrity of the data, verification of the source, and relevancy of the information are the three most important criteria for trustworthy content (against the requested one). The goal is to reduce the amount of data that can be verified, the amount of time it takes to verify it, and the amount of computing resources required for signature formation and verification [15], the producer selects a suitable signature method (such as RSA [43], EC-DSA, or EDDSA [43]) from a huge fixed set. It is possible that the process of verifying signatures will include numerous rounds of retrieving certificates and checking them. As a result, one of the potential solutions is to store in a cache the verified certificates that are necessary for verification and that may be utilized up to the point that they expire [15]. The public key is stored in every signed data packet file for further verification. The cryptographic digest of the public key, sometimes known as a fingerprint, and a key locator that identifies the location of that key are also connected to the signed data packet.

NDN employs content encryption as a means of facilitating access control and maintaining confidentiality. On the other hand, trustworthy servers or directories are not required in order to put access control rules into effect. Additionally, there is no need to disseminate the decryption key since it may be provided together with the material. The NDN network is capable of symmetric and asymmetric encryption. The private key is required in order to decrypt any content that was encrypted using the public key. If the material is encrypted using symmetric keys, then it is necessary to have a secret key, which may be retrieved from a signed interest packet if it has been authenticated. A data producer is able to validate the consumer via the use of its signature, and it provides the consumer with an encrypted secret key by making use of the customer's public key (visible to consumer only).

The symmetric key of the two communicating parties is used to encrypt or sign NDN packets, as stated by Shang et al. [44]. Access control is essential in order to discern between users who are doing legitimately and those who are acting maliciously. It enables content creators to publish their work in any namespace, and it enables content consumers to access whatever material they choose as long as they have the correct key. An existing method of access control known as UCONABC [45] has been improved upon by Hamdane et al. [46] in order to provide data-centric access control in NDN that is both optimum and safe. The definition of access rights management over NDN is done with the help of UCONABC. Information is protected by encryption and passwords in this paradigm, with access managed by an ACL (ACL). With the suggested method, only authorised readers and writers may have access to protected information. When it comes to protecting the confidentiality of NDN interest packets, Massawe et al. [47] suggest a scalable and privacy-preserving routing protocol based on Bloom filters. As an added bonus, a multicast key management system is developed. For key distribution, a content-aware key tree is employed. To ensure the safety of ChronoChat, a chat application developed at UC Berkeley for use on NDN. To ensure the security of this system Yu et al. [48] suggest a Web-of-Trust (WoT)-based endorsement-based key management system. Here, users may verify the membership of other users and the authenticity of users in the chat room without relying on a third-party public key infrastructure.

#### **2.1.1.4.2 Trust management**

Trust is used in a network to authenticate a key for a packet without requiring a central clearance mechanism. Pournaghshband, et al. [49] devised a mechanism for users to securely get the content producer's public key ( $K_p$ ) from their community of trust. When a data packet is sent to user  $U$  and  $K_p$  is either not cached or found to be invalid, user  $U$  will query its CT for the location of  $K_p$ . The replies received from Connecticut are checked against the local policy. In addition, a key revocation strategy has been implemented for this model in order to get rid of old keys that have either reached their expiration date or have been revoked. Applications such as the secure communication tools, [50], [51], industrial automation, and networked control systems utilize NDN's trust management capabilities [52], [53], [54]. Yu et al. [55] developed a series of trust schemas tailored for various NDN.

#### **2.1.1.4.3 Privacy**

It is necessary to encrypt the content as well as the name of the material in NDN in order to provide privacy, for example in the same way as ANDaNA [56] does. In the current version of the Internet, identification of content consumers is straightforward through the utilization of IP addresses and payload. In NDN, monitoring "requested data" is simplified due to naming and caching mechanisms. However, without a destination address, discerning the entity requesting the material becomes challenging, unless there's a direct connection. The requests made by users are stored in NDN routers, making them susceptible to attack. As a result, NDN necessitates the implementation of privacy at the router level [16].

#### **2.1.1.5 Mobility**

In an IP-based system, devices require an IP address for each networking interface they utilize or for topological changes to enable interaction with other devices. However, having an IP address does not guarantee the maintenance of a continuous connection. Therefore, communication is not going to be possible for mobile devices unless they find a way to consistently get a new IP address whenever they move to a new place. Mobile IP [57] and Host Identification Protocol (HIP) [58] are two alternatives that have been developed in order to address this issue; however, none of these protocols directly address the problem of content mobility. The rerouting of traffic is handled by these systems via the use of topological information and indirection points [59]. NDN, on the other hand, allows data to be accessed using content names (CNs) rather than IP addresses. Since of this, mobile users are able to have improved data access because it is no longer necessary for them to continuously obtain an IP address. Additionally, mobile users are able to continue communicating with one another regardless of whether or not published information is available. The following table provides a brief summary of the primary distinctions between IP-mobility and NDN mobility difficulties [60].

##### **2.1.1.5.1 Host Multi-homing**

When using the Internet, each program is needed to create their own separate connections using a variety of network interfaces (Bluetooth, Wi-Fi, etc.). Each interface needs a one-of-a-kind IP address in order to fulfil its function of making communication easier, as well as to fulfil the conditions necessary to keep a TCP connection open. As a consequence of this, switching between the various network interfaces is made more difficult due to the fact that each interface has its own unique IP address. There is support for the name from NDN. As a result, NDN programs are able to investigate many network interfaces since they may submit requests to all of the interfaces simultaneously.

#### **2.1.1.5.2 Network Address Consistency**

When it comes to Internet Protocol (IP), routing protocols are required to keep the routing tables in the network consistent. This requirement results in a significant increase in network overhead for large-scale networks, such as slow convergence in BGP and limited scalability in OSPF.

#### **2.1.1.5.3 Connection Oriented Sessions**

Resuming communication after a node relocation on the modern Internet requires re-establishing the TCP connection. However, NDN does not connect to the data source in order to facilitate communication. Additionally, NDN does not keep sessions.

#### **2.1.1.5.4 Scoping of What and Where**

The location of a customer should not be used to identify them. The BBC iPlayer service, for instance, restricts access to users with IP addresses based in the United Kingdom, limiting their freedom of movement. No Dependent Networking (NDN) allows users to access content based on CN rather than physical location.

#### **2.1.1.5.5 Resilience through Replication**

If either the host identification procedure during connection initiation or any intermediary router procedure fails, no information will be transmitted through IP. During the course of NDN, the requested data is stored in the cache of an intermediate

router, which then processes the request if the cached data is still valid. Meisel et al. [60] were among the first to assert that the Internet's structure and protocols were not tailored for highly mobile environments like Mobile Ad-hoc Networks (MANETs). They subsequently delved into analyzing the chief reasons for failure of IP-routing based approaches in accommodating mobility, a topic we've extensively addressed previously. To address these issues, a number of IP-routing based protocols that make the most of wireless broadcast were developed. Unfortunately, there were still issues with managing mobile nodes and assigning IP addresses to them. DTN is a novel approach that replaces node IP addresses for names, by placing data units into bundles. Still, the standard IP addresses are used for the distribution of each package.

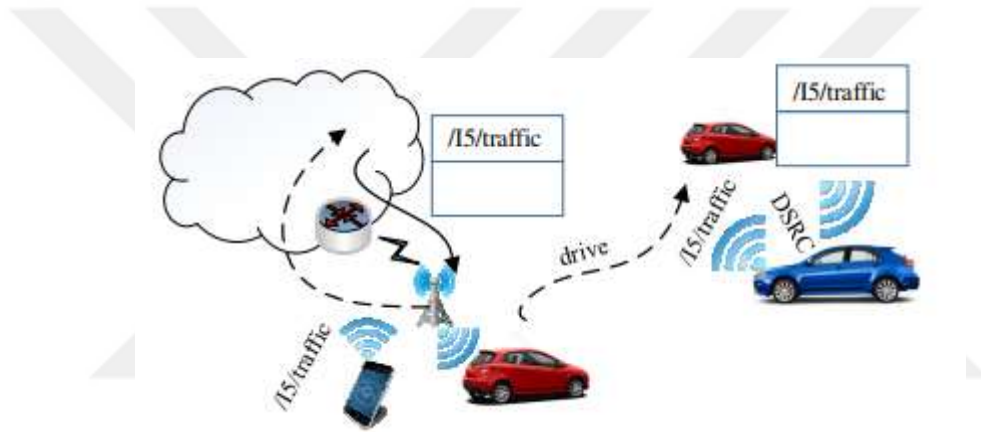


Figure 2.7. An illustration of Delay-Tolerant Networking (DTN) and its interaction with connected networks [14]

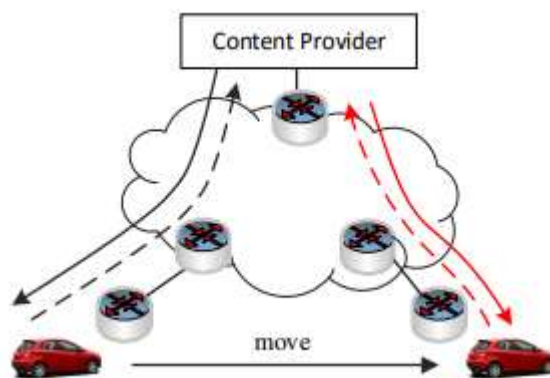


Figure 2.8. Data flow along the backward path of the IP packet [61]

While in the present Internet, DTN and MANET data delivery are handled by two different sets of technologies, in NDN, they are integrated into the architectural design. In addition, a distinctive feature of the NDN is that it obviates the need for an Internet service provider (ISP) in order for devices to interact with one another as long as they are either physically close to one another or connected to one another through device-to-device pathways [62]. Figuratively speaking, a scenario is shown in Figure 2.7 to examine the communication between mobile nodes in NDN under varying connection circumstances. Let's say a mobile phone makes a request for traffic information through Wi-Fi. Mobile-nodes or vehicles in the area might potentially overhear the response and store the information for use in responding to similar questions in the future. Without wireless coverage, these mobile nodes / cars may nonetheless provide other vehicles with stored data about traffic conditions whenever they meet them via V2V communications [63].

Because of its in-network caching capabilities, NDN facilitates user mobility with little effort on their end. To provide a seamless handoff, content requests are cached across routers in the event that a consumer moves to a new location, as seen in Figure 2.8. NDN provides built-in mobility support for consumers, but not for content creators [28], [64]. It has been suggested that a dynamic framework be developed, as done by Azgin et al., in order to measure the effect of producer/consumer mobility on network performance [28], [64].

The authors suggested using the Constant Bit Rate (CBR) traffic model, which is useful for simulating delays in both delay-sensitive and delay-tolerant traffics. Interest packets are transmitted at a set interval in delay sensitive traffic, however in delay tolerant traffic, data is forwarded opportunistically, which means that a node will transfer the data anytime it establishes a network connection. The impact of mobility on NDN, both within and across ASs, has been analyzed by the authors. Mobility in data consumption entails the transmission of interest packets before to the handoff and the retrieval of related data after the handoff. In order for data producer mobility to work, it is necessary to transport the interest packet to the new location of the data producer. Supporting a seamless hand-off for mobile nodes that are moving quickly inside NDN is another important topic. As a result, we have divided the mobility of

NDN into two major categories: the mobility of producers and the management of hand-offs, as indicated in Figure 2.9.

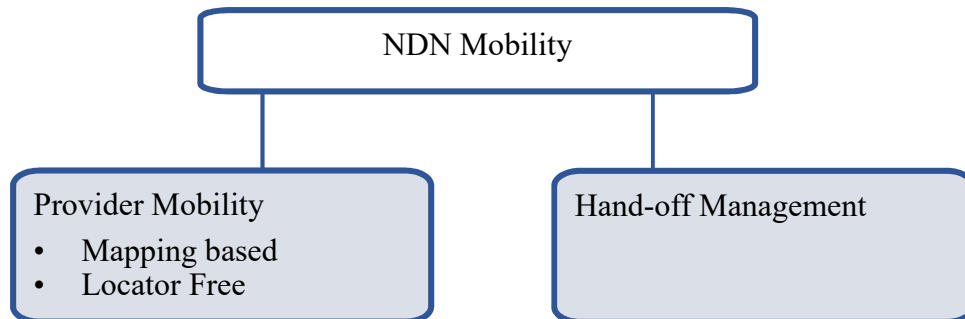


Figure 2.9. Classification of NDN Mobility Techniques.

## 2.1.2 Open Research Challenges

Because NDN is still a relatively new area of study, it presents both the researchers of today and those of the future with a wealth of unsolved research problems.

### 2.1.2.1 Naming

The design of the NDN should provide support for names that are globally unique, human-readable, secure, and independent of location [15]. As a result, the most important challenge is to create a naming system that is capable of meeting all of these needs. Some of the criteria may be met by using naming systems such as flat naming, hierarchical naming, or attribute-value naming, which are already available. Flat names guarantee originality and don't need any further work to locate the most extensive possible prefix match. Flat names have the potential to be self-certifying and are able to be readily managed using highly scalable structures, such as DHTs. On the other hand, name aggregation cannot be performed with flat names. The usage of flat names results in an increase in the size of the routing table, which in turn decreases the scalability of the network. However, there has been no explicit study conducted to determine whether or not flat names can deliver the requisite performance. Both human readability and the ability to aggregate names are benefits of using hierarchical

naming. As a result, the routing table size and update time are both reduced, and the network's capacity may be increased. Hierarchical names, on the other hand, do not completely enable persistence because of the aggregate of names. Similarly to NDN, CNs displays content characteristics in an explicit manner.

The CN will be updated to reflect any change in the content hierarchy, be it because the owner changed or because a content provider made any modifications [58]. Since the packets may be routed in the same way as the Internet, a hierarchical naming scheme is used to guarantee that each name prefix is unique. An important problem with hierarchical naming is the transparency with which its names reveal the features of its contents.

According to Bari et al. [28], it is recommended to make use of self-certifying flat names since these names provide authenticity, uniqueness, and persistence. However, there is not yet a widespread consensus over the naming technique that ought to be employed, and the matter continues to be one that calls for more study. On the other hand, users are interested in accessing the material via the use of human-friendly names, which do not fulfil the restrictions set out by the network. As a result, the investigation of naming procedures for NDNs remains a significant and crucial problem. Memory use is significant due to the fact that NDN forwards packets via CN, where the length of the name may vary and is not limited in any way. Because of this, the fast pace at which the FIB is updated creates a scalability difficulty for the name resolution. There is also the possibility of using hashing to convert the CNs into a fixed integer format, such as an IP address, and then using IP-based routing techniques in order to forward the data. Despite the fact that many such systems have been presented, there is still a need to design at least one flexible and realistic method (or more than one), in order to enable efficient data transmission at the router level.

### **2.1.2.2 Routing**

In the NDN, the development of protocols for inter-domain routing is still an unsolved research problem. In addition, the implementation of the recommended routing techniques at the Internet level is the issue that poses the greatest challenge. Inter-domain routing over the Internet is accomplished by the use of the BGP protocol. BGP is based on rules rather than the shortest pathways, and it is the protocol that is

utilized. Because of the frequent changes in policy agreement that occur in NDN, the creation of inter-domain routing is a tough endeavor. Error control, fault detection, and recovery are all tasks that fall within the purview of NDN's forwarding plane. Only bootstrapping forwarding and long-term topology propagation have reduced routing's prominence in NDN. As a result, there is a pressing need to do further research into the forwarding and routing sectors of the Internet, both of which are now absent. In addition, traditional routing may be substituted with geometric routing, also known as hyperbolic routing [16] for NDN in order to solve the issue of scalability in the routing process.

In place of a comprehensive routing database, this approach calls for the use of a service that converts names into hyperbolic coordinates. However, until this point, the performance of hyperbolic routing and the capacity of hyperbolic routing to manage complex routing rules across ISPs have received a very limited amount of attention. Nodes are more likely to relocate often in highly dynamic networks. In NDN, data packets follow in reverse the route that was taken by their respective interest packets. In the event that an intermediary node alters its position subsequent to the transfer of the interest packet, the reverse route will adjust accordingly to accommodate the node's new location. Consequently, effectively managing NDN mobility within a highly dynamic network warrants further investigation.

### **2.1.2.3 Caching**

When numerous diverse types of traffic vie for a restricted cache space, the NDN faces a significant difficulty in the area of cache-space management. Despite the development of numerous selective caching techniques for NDN architecture, there is still ample opportunity for academic research in this area. Selective caching divides the network's traffic into popular and less popular items, but implementing this technique can be resource-intensive. Other criteria for selective caching include avoiding caching material that is sensitive to privacy, caching just the most popular content (in the network), and periodically replacing information that is less popular. As a result, the most difficult aspect of research is determining the popularity of information in an accurate manner while using as little resources as is practically feasible. Dealing with the issue of false popularity of material is another difficulty that

is related with selective caching at the same time. Additionally, the use of caching and replication strategies inside the network makes it feasible to concurrently enhance routing, forwarding, and management of in-network caches. This is made possible by the usage of methods within the network. For example, routing decisions might be influenced by cache locations, the capacity for information storage, and signals indicating cache competition. Due to cost and performance concerns, router caches are maintained at minimal sizes.

In order to create way for new material that is more popular, content replacement rules are implemented. These policies also delete information from the cache that is less popular. There is a give-and-take relationship between the processing capacity of the router and the level of complexity of the cache replacement rules. Because of processing limitations at the router, these regulations need to be simplified as much as possible. Although there are already a great number of complicated content replacement rules, there is still a need for the creation of content replacement policies that are capable of being scaled at the Internet level. In mobile systems such as MANET and DTN, the expense of managing these cached copies adds to the overall cost, but more recent mobile routing algorithms offer opportunistic on-path caching. As a result, one of the current challenges in the field of study is the development of routing algorithms that may reduce the expense of maintaining routing information in order to access cached materials. Another outstanding question is how to handle unpopular information, which does not profit in any way from caching since it is not often accessed. According to the findings published by Varvello et al. [65], the inclusion of less popular items diminishes the overall performance improvements provided by structured routing algorithms.

#### **2.1.2.4 Forwarding**

At the NDN router, there are a variety of data structures that may be used to construct the PIT and FIB. However, there is still room for improvement in this study field in terms of the development of effective data structures that allow minimal memory usage and high-speed lookups. As previously discussed, the forwarding methods explore the multi-path capabilities of NDN and select the optimal outgoing interface(s) to forward the interest packet. It is able to identify several assaults,

including prefix hijacking and DDoS, in addition to supporting load balancing across pathways, congestion management, and link failure [13], [66]. There are still many obstacles to overcome in order to build forwarding techniques that are successful and efficient for a variety of networks and settings. Since the NDN forwarding plane now handles tasks previously managed by IP's transport layer, NDN does not possess its own distinct transport layer.

Working with data within the network with NDN requires more processing in within the routing process. This contributes to a heightened complexity in data transfer compared to the traditional Internet model. Although several approaches have been proposed for analyzing these innovative mechanisms' capabilities, further research into the design of flow, congestion, and error control functions is necessary. Investigating the best technique to make use of the potential of several paths at once is still another unresolved challenge.

#### **2.1.2.5 Mobility**

The current architecture of the Internet is still having trouble supporting mobility, whereas mobility in NDN should be explored. Mobility for end users is built into the NDN, but mobility on the part of service providers creates overhead and scalability problems. When a provider changes location, the information in their locator needs to be updated. The effect of the provider's mobility can be mitigated by caching and replicating popular content, but less-used content will continue to be negatively affected by this.

NDN mobility reduces the time it takes to switch between the consumer and the real provider by making use of cached and duplicated copies of the material held by an intermediary node. However, the primary issue is that caching is not widely used in real-time communications (e.g., a voice call). As a result, providing NDN with real-time support for multimedia applications is a significant area of study. The cars rely on crowd-sourced data almost exclusively. Given this, it is crucial to protect the privacy of the data source while yet ensuring data authenticity.

### 2.1.2.6 Security, Privacy and Trust

Because NDN negotiates transactions directly with CNs, all of the content properties are kept in their original state. As a result, ensuring the privacy and safety of the material is an ongoing research problem. Encryption with keys connected to CN is used for the purpose of providing security in NDN architecture. There is a paucity of written material pertaining to key management, or the question of who will be in charge of key generation, distribution, and revocation. This involves establishing access control rules, enforcing access control policies for cached content, and authenticating users [15]. When all nodes between a user's node and the content provider can access the user's content requests, an adversary could exploit this information to track the user. There is currently no provision for a long-term solution. In conclusion, privacy, trust management, and other aspects of security are still available for investigation inside the NDN.

## 2.2 Ant Colony

The concepts behind Ant Colony Optimization (ACO) are inspired by how ants naturally navigate between their colony and a source of food [67]. Ants use increased pheromone trails that they leave behind to communicate. The shortest path will draw the most pheromones [68]. An artificial swarm intelligence system is called The Ant Colony. Stutzle and Dorigo created the first ant-based algorithm, called Ant System [69]. In a variation of the twin bridge experiment where one bridge is substantially longer than the other, Goss et al [70] looked at this issue in Figure 2.10. In this instance, the ants who just so happened to select the brief bridge get at the nest first. As a result, the shorter bridge gains greater pheromone density than the long bridge, which increases the likelihood that it will be chosen [71].

$R_1$

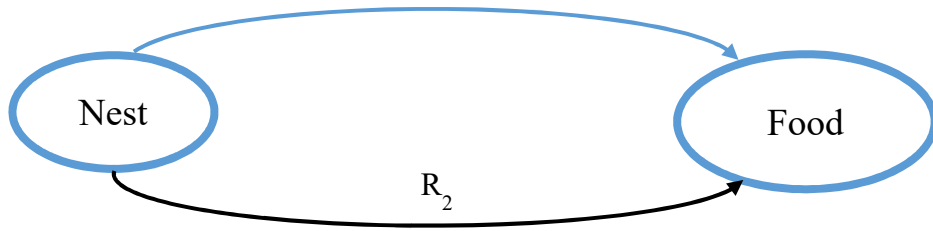


Figure 2.10. Ant Colony (AC) chooses between two bridges with different lengths  $R_1$  and  $R_2$  [68].

In order to construct a probability model of the observed behavior of ants, it was decided [72] to let the other ants choose it first. If we assume that  $m_1$  ants crossed over on the first bridge at a particular time and  $m_2$  ants crossed over on the second bridge, then the probability that an ant would cross over on the first bridge is calculated as follows:

$$p_1 = \frac{(m_1 + k)^h}{(m_1 + k)^h + (m_2 + k)^h} \quad (2.1)$$

The experimental results in a shorter and less congested path may be created by changing this  $h$  and  $k$ .

The probability of the other bridge in the twin bridge experiment is  $p_2$ . that is

$$p_2 = 1 - p_1 \quad (2.2)$$

Ants migrate through the network from one node to the next. The likelihood of the next hop is computed based on the pheromone amounts that the current node has placed on the edge and broadcast [73].

After inspecting all nodes, a satisfactory solution is reached as each ant originates from the same starting node. The ants complete their individual solutions and update the pheromone trails. Meanwhile, evaporation leads to a decrease in pheromone levels [74]. During the evaporation process, pheromone concentrations gradually diminish. Conversely, segments of the network with the most optimal solutions experience an increase in pheromone values.

Perhaps one of the first routing algorithms to use ACO is AntNet [75]. In AntNet, a group of mobile agents simultaneously explores the network and transmits data to the nodes to update their routing tables. This works as follows: at regular intervals, a single ant is sent out to explore. Each node in the network is a junction, and contains

two things: a routing table and a traffic table. The routing table shows the probability that an ant will go to any neighbor node after arriving at this node, based on the desirability of each neighbor node. The traffic table tracks traffic conditions at each node, the average and standard deviation of the number of ants in line. The ant uses the equation below to decide which direction to continue in:

$$p_k(r, s) = \frac{T(r, s) + \alpha E(s)}{1 + \alpha(N + 1)} \quad (2.3)$$

where  $p_k(r, s)$  is the probability that ant  $k$  will move to node  $r$  when it is currently at node  $s$ .  $N$  is the number of neighbors of this node, the factor  $T$  represents the trail that has been established by prior ants and is the number in the routing table. The factor  $E$  represents the current congestion level of the link according to the function

$$E(r, s) = 1 - \frac{q_n}{\sum_{k=1}^N q_k} \quad (2.4)$$

Once the ant reaches its destination, it will turn around and move backwards. It will update both the routing table and the traffic statistics at each node on its way back.

Baran and Sosa [76] later made some updates to this algorithm to provide smart initialization, handle the case of link failures and introduce some randomness to prevent complete convergence. DiCaro used similar ideas to improve AntNet and design an algorithm AntHocNet [67] which was shown to outperform AODV.

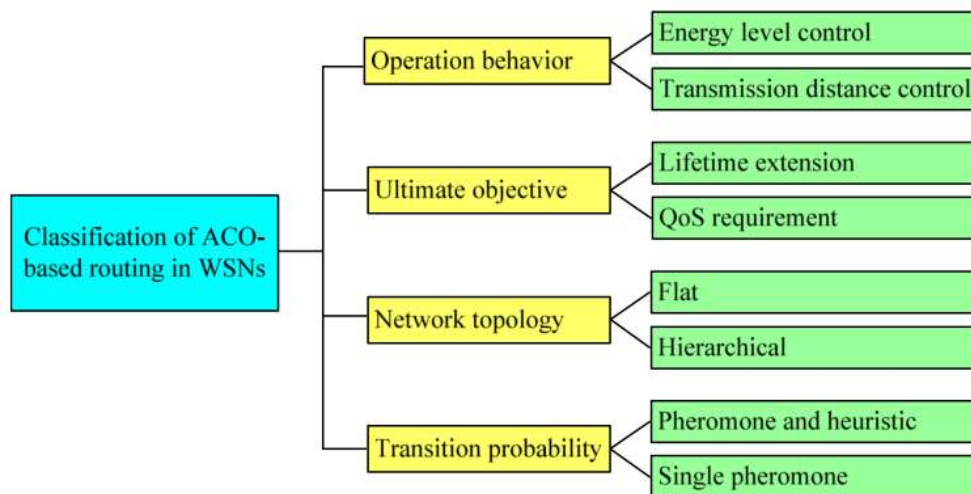


Figure 2.11. ACO based routing

Xunxun Liu [77] provides a survey of the work in applying ACO for routing in wireless sensor networks. Liu provides a classification of these routing algorithms as depicted in Figure 2.11. The algorithms are classified based on whether the network topology is flat or hierarchical, whether the energy level or transmission distance is being controlled and whether the objective is lifetime extension of the network or some other QoS requirement. The method by which the transition probability is calculated is also considered. The paper considers ten different algorithms proposed between 2006 and 2016. These algorithms are BABR and EEABR, ACO-QoS [78], E&D ANTS [79], EAACA [80], ASTRL [81] UMM [82] ODTs [83] and MMBEC [84].

Breakthroughs in unicast and multicast routing protocols utilizing ant colony optimization are discussed. Mangai et al. [85] introduced the source-initiated Dynamic Core-based Multicast Protocol (DCMP), leveraging ant colony optimization. There are three types of sources that may be specified in DCMP: core active sources, passive sources, and active sources. Passive sources are those that do not actively contribute to the data. Mesh maintenance is conducted in a soft state, akin to the On-Demand Multicast Routing Protocol (ODMRP). In NS2, there are 50 nodes that move about in an area that is 1000 m<sup>2</sup> by 1000 m<sup>2</sup>, and the speed of the nodes ranges from 0 to 20 meters per second. The stop duration is 10 seconds. Our working assumption is that the simulation will run for a duration of 600 seconds, with a constant bit rate (CBR) traffic load of 10 packets per second. The findings suggest that there was an increase in the percentage of successfully delivered packets and a decrease in the amount of control overhead in proportion to the speed of the node.

Li et al. [86] introduced an enhanced ant colony-based approach for multi-constrained Quality of Service (QoS) routing. During the process of seeking, there are two distinct groups of ants that each carry out their own search. One method identifies the most efficient route from the source to the destination, while the other identifies the most efficient path from the destination back to the source. Following the completion of one search, they share information in order to prevent stagnation. The two possible routes that combine many QoS constraints are compared, and the best one is chosen. During each iteration of the search process, the previously obtained optimum route as well as the probability of the path are both stored. The likelihood of

the ant's previous search is included into the process of choosing the next node that each ant will investigate in order to expedite the search. The ideal route is determined to be the one that both satisfies the QoS conditions and has the lowest possible cost, and the output is the multicast tree with the lowest possible price. For the purposes of the simulation, eight nodes are chosen, and the features of each node are characterized by four vectors, as follows: (delay, delay jitter, bandwidth, cost). In comparison to the small delay method, the proposed technique has a longer latency but lower overall costs (which provides minimum delay). In comparison to the minimal cost algorithm, it has a higher cost but a lower latency (which provides minimum cost).

A multi restricted QoS routing model was proposed by [86], with mobile agent functioning as the node. Orthogonal experiments and statistical approaches are used to determine the influence of QoS factors. An appropriate orthogonal table is built in accordance with the overall scope of the search route in order to check the influence of each and every quality of service parameter. The dynamic volatility of the pheromone introduces a refined metric to expedite convergence and construct an optimal multicast tree that meets multiple Quality of Service (QoS) requirements. The orthogonal table L9 (34) is chosen to use since it best fits the parameters of the search route. In this case, the number of searches is denoted by the numeral 9, the number of qualities of service characteristics is denoted by the numeral 4, and the number of levels regarding the searching route is denoted by the number 3. In the simulation trials, eight nodes are selected using the restricted function of the four-dimensional vector as the input (D, DJ, B, C). An algorithm may swiftly arrive at the best answer while simultaneously satisfying a number of QoS restrictions.

The hybrid multicast routing protocol was introduced by Liu et al. [87] in order to enable QoS parameters with ACO. Improved Zone Routing Protocol (ZRP), which is used to create an optimal network architecture that satisfies the Quality of Service standards, is used in mobile networks because of the peculiarities of mobile networks. Calculations are made to determine the multicast route based on the topology. The ant colony technique is then used in order to construct the best possible multicast tree. There are fifty nodes moving about in an area that is one kilometer by one kilometer at a speed of zero to ten meters per second, and the transmission radius is one quarter of a mile. The simulation duration is set at one minute and fifty seconds, and the

capacity of the channel is 2 Mbps. A comparison is made between the performance of the algorithm and the protocols known as Ad hoc On demand Distance Vector (AODV) and Destination Sequence Distance Vector (DSDV). The approach has the potential to significantly cut down on the average latency while simultaneously increasing the pace at which packets are delivered.

An Ant agent based Adaptive Multicast Routing Protocol was suggested by Sabari et al. [88] (AAMRP). It takes use of the fact that members of the group want to simplify multicast routing in order to trigger broadcast operations in the appropriate locally regulated environments. Reducing the participation of group members in building the multicast structure and enhancing mobility through broadcasts in densely populated local areas increases resilience. The suggested protocol is able to obtain statistics on the delivery of packets that are equivalent to those of a pure multicast protocol while also having a substantially reduced overhead. AAMRP will dynamically identify the members of the group and arrange them into clusters that correspond to locations where there is a strong affinity between group members. One of the individuals inside the group in each of these "dense" communities is chosen to take on the role of cluster leader. A sparse multicast structure is established between the cluster leader and the source by the leader of the cluster. They distribute the packets to the members of the other groups in their cluster by broadcasting the information. The AAMRP allows each member of the group to be in one of three states. It is possible for it to be a transient node that is just starting the session, it is possible for it to be a cluster leader, or it is possible for it to just be a member of a cluster. Each node is responsible for keeping its own Group Member Table (GMTTable), and the cluster leader is also responsible for keeping a Cluster Member Table (CMTTable). In the NS2 simulator, 25 nodes, 50 nodes, 75 nodes, and 100 nodes all move at a pace of 10 meters per second inside a zone that is 600 meters by 600 meters. In these simulations, the Random Way Point (RWP) model is employed alongside Constant Bit Rate (CBR) traffic, with a 250-meter node transmission radius. Variations in node count and group size are analyzed with respect to control overhead, routing burden, end-to-end delay, and packet delivery percentage. The strategy effectively enhances the percentage of packets that are successfully delivered while simultaneously reducing the end-to-end latency and the routing burden.

A technique for constructing a multicast tree was given by Gong et al. [89] in which ants methodically forage from each destination node, search the tree, choose an optimal path, and put the nodes and edges encountered along the way into the tree. Once all of the intended recipients have joined, the multicast tree may be constructed. Quickly determining the ideal or nearly perfect solution is possible with the use of algorithms. Simulation studies assume a network with a size of 100 nodes, with the distance between any two nodes standing in for the cost of an edge. Edge delays are measured between 0 and 10, whereas delay jitter is recorded between 0 and 1. (0, 5). According to the test findings, the algorithm outperforms the ACO method in terms of constructing a multicast tree with a minimal overall cost in a relatively short number of iterations.

Improved Ant Colony Algorithm was a proposal made by Liu and Song [82] (IACA). It provides many solutions for resolving QoS routing issues, such as altering the pheromone update algorithm and exchanging the probability constant that ants pick when selecting a route for the piecewise function  $Q(t)$ , which stands in place of the probability constant. The number of steps at which an algorithm is improved may be defined as such. The first step is to determine the minimum and maximum values for the pheromone. In stage two, instead of  $Q$ , you should write  $Q(t) = \log(t+1)$ . This is because  $Q$  is dependent on stage one. Use the piecewise function  $q_0(t)$  instead of the constant  $q_0$  that was selected by the ants based on the stage two data in stage three. We advise starting the iteration with a lower value for  $Q(t)$ . By keeping the pheromone increase along each path to a minimal, we may avoid the potentially disastrous effects of too positive feedback. To speed up convergence,  $Q(t)$  is raised to a larger extent in succeeding iterations. In order to identify the ideal solution interval as rapidly as possible, the algorithm maximizes the size of the search space and takes full use of the available information to narrow its emphasis to the ranges that are most likely to include high-fitness people. Set the algorithm's parameters for each node's cost, delay, delay-jitter, and packet-loss, as well as the parameters for each link's cost, delay, delay-jitter, and bandwidth. For the sake of this simulation, the number of ants has been set at 30, and the maximum number of iterations has been set at 100. The results of the experiments demonstrate that the enhanced ant colony algorithm has a success rate of up to 99.81% in solving QoS routing issues, and that its ratio for obtaining the best

solution reaches up to 99.65%. The findings are far better than what could have been achieved using the standard ant colony method.

An ant colony optimization method known as ANBRA was suggested by [90] for use in the routing of ad hoc networks. The technique is based on the state of the network connection. In ANRBA, the selection of routing pathways is determined by a combined measurement value, which incorporates the accepted load rate, topology diversity rate, and routing delay time. Once the routing pathways are established, the ant colony algorithm is employed to gather measurements of these routes and dynamically update the pheromone table. This dynamic adjustment helps distribute the network load effectively. In Ns2, fifty nodes travel over a surface area of one thousand by one thousand meters at different intervals ranging from zero to three hundred seconds. It is assumed that the node speed is 10 m/s, and the bandwidth is 2 M b/s. The duration for the simulation is set at 400 seconds, and there are 10 CBR traffic connections. ANBRA achieves much superior performance in terms of the packet switching rate as well as the average delay time with variable pause times.

Ant colony based Multicast Routing (AMR) was developed by Sabari et al. [88] as a solution to the issue of traffic engineering multicasting. AMR optimises numerous goals at the same time. The algorithm will introduce an additional constraint in the cost-metrics, calculated as the product of the average latency and the maximum depth of the multicast tree. Subsequently, it will aim to minimize this combined cost metric. The ACO calculation method is used for the calculation of the shortest route tree beginning at the root. This is accomplished by employing a modified heuristic function to construct degree-bounded spanning trees, ensuring that all hosts connect to the source through a host closer to the root of the tree. Every node has to be linked to a parent that is one step farther away from the root than it is from itself. This means that if a node's parent is b, then  $dM(b, \text{root})$  has to be greater than  $dM(a, \text{root})$ . As a result, this contributes to a reduction in the delay that is caused by deviations from the best route. In NS2, the territory of 600\*600 m<sup>2</sup> is traversed by 25 to 75 nodes at a maximum pace of 10 meters per second, with a stop duration of 5 seconds between each node. The simulation takes place over a period of fifty seconds, and traffic is modelled as CBR. The performance measures include packet delivery ratio (PDR), latency

multiplied by the depth, and control overhead. The results suggest that changes in node density lead to a proportional decrease in control overhead and routing overhead.

A method called Ant-based Multi-objective On-demand QoS Routing (AMQR) for Mobile Ad-hoc Networks (MANETs) has been introduced by Deepalakshmi et al. [91]. This algorithm is extremely adaptable, efficient, and scalable, and it decreases end-to-end latency in circumstances of high mobility. The proposed method includes stages that are labelled as "route maintenance" and "route discovery." In the immediate area, ant-like packets are employed to discover new pathways. The communication cables between neighbouring nodes are sprayed with an artificial pheromone. Route reply and data packets are steered in the direction of the pheromone with the strongest signal, while the next hop is determined by random chance. Every node implementing this method maintains three tables: neighbor, path preference, and routing. Upon request, the neighbor node with a higher route preference value duplicates its entry into the routing table for the corresponding destination. In NS2, there are anything from 50 to 100 nodes moving about in an area that is 1500 m<sup>2</sup> by 1500 m<sup>2</sup>, with node mobility ranging from 10 to 80 meters per second and a simulation time of 900 seconds. Comparisons have been made between AMQR and AODV and ANTHOCNET with regard to latency, throughput, jitter with a variety of flow counts, node mobility, and a number of different pause periods. However, it has a high routing cost while having an excellent packet delivery ratio, which helps decrease latency and jitter.

An ant-based multi-path routing method that incorporates both reactive and proactive components was presented by Miae Woo et al. [92]. Both the phase of route setup and the phase of route recovery are reactive aspects. In order to prevent stagnation, the algorithm makes use of pheromone heuristic control. The length of the queue and the average amount of delay at the MAC layer are both used as factors in the heuristic function. The following are the requirements that must be met for a reactive backward ant to be formed by any lawful intermediate node; this is a distinctive aspect of the method that has been suggested. 1) There should not be any backward ants formed by any other nodes that have been visited before the intermediate node while it is travelling to its destination. 2) The information on how to get to the location should be as up to date as possible. 3) The number of hops

between the source node and the intermediary node must adhere to a specific range of values. Additionally, the proposed technique regulates the number of entries for a specific node in the routing table to mitigate routing table overhead. This is done in order to save space. Priority is given to entries that have recently updated pheromone values and entries that have been updated by backward ants that were created from the destination. In Qualnet, there are 100 nodes and 20 traffic sources that move about in an area that is 3000 m<sup>2</sup> by 1000 m<sup>2</sup>, with a stop time that may be anywhere from 0 to 300 seconds and a simulation period that lasts 300 seconds. Performance metrics such as the average number of forward ants delivered, the average number of backward ants delivered, end-to-end latency, and packet delivery ratio are considered, with varying stop intervals. The proposed approach effectively handles the overhead generated by ants, resulting in reduced end-to-end latency and improved packet delivery ratio.

### **2.3 Swarm Routing**

Swarm intelligence (SI) refers to the quality of a system in which coherent functional global patterns arise as a result of the collective actions of (unsophisticated) individuals interacting locally with their environment [3]. Without the need for a master controller or a universal model, swarm intelligence offers a foundation for investigating collective (or dispersed) problem resolution.

Nonetheless, the behavior observed in groups such as flocks of birds, schools of fish [93], swarms of bees, and colonies of ants highlights a connection between engineering applications, optimization, and swarm behavior. Foraging strategies used by ant colonies, for instance, have the potential to be used in solving shortest-path difficulties and other types of optimization issues that arise in the real world [3].

For a bird to effectively join a flock, it requires behaviors such as collision avoidance, velocity matching, and flock centering. These behaviors allow the bird to synchronize its movements with those of its fellow flock members. Problems with nonlinear function optimization and control of unmanned aerial vehicles (UAVs) may be addressed with the use of these methods. There is no need for a centralized command structure in the social insects since all of these responsibilities are successfully completed. That is, people communicate with one another by either direct

or indirect touch. The persons who are engaged do not have an overall comprehension of the responsibilities or the potential solutions. Rather, these complicated behaviors are produced as a consequence of a large number of people detecting and behaving locally in accordance with a straightforward rule [94].

However, social insect behavior as a collective may provide instructive examples of how to approach complicated system design and administration. Self-organization, decentralized control, adaptive behavior, and robustness are just some of the features of natural systems that pique the curiosity of complex systems theorists [94]. Numerous technical and commercial problems may be addressed with this simple yet effective method. Swarm intelligence techniques are being evolved into new approaches for dealing with widespread issues [95]. Natural systems like ant colonies, bird flocks, and fish schools provide as inspiration for these models. This strategy places a focus on decentralized problem solving, direct or indirect interactions amongst relatively basic agents, adaptability, and resilience. This section introduces the concepts of swarm intelligence, including an overview of ant algorithms, analytical ant algorithms, particle swarm optimization, and bacterial swarm optimization.

### **2.3.1 Properties of Swarm Intelligence**

In order to complete tasks, social insects exhibit behaviors indicative of collaborative action [94]. The key processes that influence the collective behavior of social insects when they are searching for food and performing other duties are described in the following parts of this article. In social insects, the primary characteristics that may be recognized are self-organization, positive feedback, negative feedback, unpredictability, and multiple interaction. In complex adaptive systems, such as biological systems and human organizational systems, there is a phenomenon known as self-organization, which may be seen. In the fields of biology, sociology, management science, and organizational theory [94] much research has been conducted on this sort of behavior.

The majority of the time, self-organizing systems are made up of a large number of components that are all very similar to one another. The study of self-organizing systems is best accomplished by first gaining an understanding of some fundamental modes of interaction among the system's components. These modes of interaction

encompass positive feedback, negative feedback, randomness, and multiple interactions. These components amalgamate to shape natural systems that are capable of completing difficult tasks through the use of straightforward and uncomplicated individual behavior [95].

### **2.3.1.1 Positive feedback**

A feedback system is said to have positive feedback when the system reacts to a disturbance in the same direction as the disruption [96]. Positive feedback is used by the majority of self-organizing systems; this includes recruitment and reinforcement [95]. A straightforward illustration of positive feedback may be seen in the behavior of ants as they forage for food. Ants that are travelling along a productive route encourage other ants to follow in their footsteps. When ant colonies are out collecting food, positive feedback mechanisms help the ants choose the quickest route back to the nest from where they obtained the food [74]. While foraging for food, ants leave behind a chemical signal known as pheromone for other ant colonies to find. Other ants can assess the amount of deposited pheromone and possess a natural inclination to follow the path. This method of trail construction and subsequent following represents a form of positive feedback inherent in the typical foraging behavior of ants [3].

### **2.3.1.2 Negative feedback**

A feedback system that reacts to a disturbance in the opposite direction as the perturbation is referred to as having negative feedback [96]. Numerous kinds of amplification systems make use of negative feedback in order to stabilize the operational parameters of such systems. Therefore, negative feedback functions as a counterweight to positive feedback, and it contributes to the maintenance of the collective pattern by acting as a stabilizer. There are a number of biological systems that have negative feedback, such as the baroreflex, which is involved in the control of blood pressure. Negative feedback is used in a variety of biological processes throughout the human anatomy. These processes range from the regulation of body temperature to the regulation of glucose levels in the blood. The pheromone evaporation method is used in the ant foraging process to accomplish the goal of

creating negative feedback. This trait benefits ants in recognizing routes that are less successful, and it also assists ants in exploring other new food sources [3].

### **2.3.1.3 Randomness**

Statisticians often use the term "randomness" to denote a collection of clearly defined statistical characteristics, such as independence from bias or correlation. Randomness, or the enhancement of random fluctuations, is crucial for generating innovative solutions within natural systems. Foraging ants, to give one example, make mistakes as they follow the pheromone trail. Although this behavior may appear wasteful at first glance, it actually helps ants locate new, previously undiscovered food sources where they can then attract additional workers to their nest.

### **2.3.1.4 Multiple Interactions**

When it comes to natural systems, where multiple interactions play a crucial role, no single person can find the best answers on their own. Moreover, people need to be able to benefit from both their own and others' actions. There has to be at least a certain number of people in a self-organizing system who can get along with one another. Self-organization occurs, for instance, in ants when workers use pheromone information from other ants [3].

### **2.3.1.5 Stigmergy**

Interactions between different types of insects are necessary for social insects to achieve their goal of self-organization. Both direct and indirect types of the contact are possible. Direct interactions include things like antennation, mandibular touch, ocular contact, and chemical contact, to name a few examples. Indirect interaction occurs when one individual influence the environment, and another responds to the modified environment at a later time. This form of interaction is referred to as indirect interaction, termed as "stigmergy" [3]. Nonetheless, it provides a broad mechanism linking individual and colony-level behavior: individual behavior impacts the environment, subsequently altering the behavior of other individuals. This cycle continues until the behavior of the colony as a whole is determined. The phenomenon of stigmergy, which is seen in social insects, demonstrates how complex issues may be readily resolved by substituting indirect connection for coordination based on direct

communications. This notion, which is simple yet very effective, may be used to simplify agent design and cut down on unnecessary communication between agents.

## 2.4 Empirical Review

At the optimization and control issues in wireless ad hoc and sensor networks via the lens of swarm intelligence [97]. First, using swarm intelligence methods, an examination of the newly suggested particle swarm optimization is provided. Due to the challenges associated with theoretical analysis involving random parameters, prior stability investigations of particle swarm optimization have been limited to this assumption. Without making these limiting assumptions, we use Lyapunov stability and passive systems principles to examine the stability of the particle dynamics. Particle swarm optimization then takes care of the problem of where to put the sink nodes in sensor networks. We also take a look at mobile ad hoc network routing methods that are based on swarm intelligence. Two protocols have been built and included into the NS2 network simulator, drawing inspiration from the search strategies used by actual ants.

The first protocol relies on a routing table that is impacted by mobile nodes to determine which node will route packets. A crucial component of mobile ad hoc network route changes is the ability to predict the neighbor node's movement via the use of HELLO packets; this is similar to how pheromone decay works in biological systems. Although functionally indistinguishable from the first protocol, the second one places more emphasis on the drain rate and remaining energy of adjacent nodes than on their mobility. This research makes it very evident that swarm intelligence techniques may be a powerful tool for solving the management and control issues that plague wireless ad hoc and sensor networks.

Ant colony-based Multicast Routing (AMR) was developed by Sabari et al. [88] optimize many goals concurrently and so address the traffic engineering multicast challenge. As a whole, the algorithm's goal is to reduce the maximum multicast tree depth and average delay to a single, minimized cost measure. The ACO algorithm determines the shortest route from the root of the tree. In order to ensure that all hosts are linked to the source via a host that is reasonably close to the root, degree

constrained spanning trees are constructed using a modified heuristic algorithm. Since node (a) can't be connected to a parent (b) that is further from the root than it is, the distance between the two must be more than the distance between the two nodes themselves.

As a result, less time is lost as a result of taking a route that isn't the fastest one. With a maximum speed of 10 m/s and a stop interval of 5 seconds, NS2 allows for the movement of anywhere from 25 to 75 nodes across an area of 600\*600 m<sup>2</sup>. We model traffic as CBR flows and run the simulation for 50 seconds. The PDR, the latency times the depth, and the control overhead are the key performance indicators. Researchers found that by adjusting the number of nodes, they may improve the packet delivery ratio while cutting down on management and routing overhead.

In the context of MANET, Deepalakshmi et al. [91] proposed an Ant-based Multi objective on demand QoS Routing approach (AMQR). This method is very adaptive, efficient, and scalable, and it reduces end-to-end latency in situations when there is a significant degree of mobility. The proposed method consists of two stages: determining and maintaining the best path. Local route discovery is accomplished by "ant-like" packets. Route replies and data packets are biased towards strong pheromone, and the next hop is determined stochastically by laying artificial pheromone on communication lines between neighboring nodes. The technique relies on three tables stored in each node: neighbor, path preference, and routing. On demand, the routing database for a given destination will be updated to reflect the neighboring node with the highest route preference value. The NS2 simulation lasts for 900 seconds, during which time 50–100 nodes cover an area of 1500–1500 m<sup>2</sup> at speeds of 10–80 m/s. Delay, throughput, jitter with different flow counts, node mobility, and stop periods have all been studied for AMQR with AODV and ANTHOCNET. However, it has a large routing overhead despite its high packet delivery ratio, lower latency, and lower jitter.

Bibhash Roy et al. [98] outlined a method that combines the Optimized Link State Routing (OLSR) protocol with the idea of ant colony optimization in order to find many stable paths between source and destination nodes. There are both reactive and proactive parts to the algorithm. During a data session, various pathways may be chosen from during the reactive path creation phase to establish a connection between

the source and the destination. Multiple nodes are selected with the use of ant agents, and those nodes then utilize more ant agents to communicate with intermediate nodes.

Routing protocols in NDN networks are analyzed and simulated at length by Yi et al. [33]. The routing process involves the dissemination of topology and policy information, both at the outset and as they evolve over time, and the generation of a routing table to direct packet forwarding. While routing used to be responsible for handling temporary fluctuations in the network, this is no longer the case now that the forwarding plane can identify errors and recover fast. NDN is able to employ routing protocols that were formerly deemed inappropriate for actual networks since they are no longer subject to short-term churns, dramatically improving their scalability and stability in the process.

According to research conducted by Saxena et al. [14], the Internet was first designed as a packet data network. On this network, users and data providers (servers) each had their own unique IP addresses, and they communicated with one another over a channel that had already been set up. In more recent times, this traditional way of data connection between clients and servers has morphed into a peer-to-peer mode of data sharing. The concept of user-generated material has been fundamentally altered by the proliferation of user-friendly applications such as YouTube, Bit Torrent, and social networks. Users in today's world are only interested in certain data pieces, regardless of where they came from. Therefore, the concept of identifying servers hosting specific material by employing IP addresses is becoming less significant as time goes on. In addition, a lack of IP addresses is a difficult problem that has been plaguing the Internet community for a very long time. Named Data Networking (NDN) is one solution that has been offered in response to the current need for a content-centric networking platform that places less emphasis on the significance of the data hosts. Users of NDN are able to float a data request without having any prior knowledge of the organization that is holding it. NDN is able to more effectively manage user mobility and security concerns than the present Internet does. Despite the fact that NDN was suggested in 2010, there is not yet a survey article that studies its architecture and the numerous schemes that have been presented for its various distinguishing characteristics. These distinguishing features include naming, adaptive forwarding and routing, caching, security, mobility, and many more. In this research,

the authors provide an original taxonomy that may be used to investigate NDN properties in more detail. Additionally, they have covered a number of NDN applications. They concluded by conducting a poll, in which they designate a collection of open issues that scholars ought to address at some point in the future.

Swarm intelligence (SI), according to Chakraborty and Kar's research [99], is becoming more important in the field of artificial intelligence (AI) as the need for solutions to more complicated problems grows. This research seeks to give a comprehensive assessment of eight different SI algorithms, as well as describe the governing notion, determine the prospective application domains, and suggest probable application regions. Insect-based and animal-based algorithms, both of which were recently created, are the focus of the research paper's discussion of their minute-by-minute development. To be more precise, they concentrate on the algorithms that were motivated by things like ants, bees, fireflies, glow-worms, bats, monkeys, lions, and wolves. The inspiration studies performed on these algorithms provide information on the operations carried out by these algorithms. Following the completion of the inspiration study, many iterations of these algorithms were developed. Researchers that are interested in the topic have also been provided with specific areas that have been identified as possible applications of such algorithms. This research tries to give a foundational knowledge for the further investigation of the technical features of algorithms and the potential applications of those characteristics in academics and in practice.

The research done by Descamps Vilà, [100] demonstrates how the many routing approaches that have been offered to overcome this issue go in very different ways. A deterministic link-state and a broadcast system are two examples of the methods covered here. Given the similarities between the two concepts, the literature review suggests that Name Data Networking, an ICN research project, might theoretically use a swarm method to its routing and forwarding planes. As a result, these methods are being investigated in depth in preparation for the presentation of a design proposal that would implement them. This design proposal would apply the characteristics of an ant-based system and conform to the NDN architecture. A simulator, which is built using several rounds of design implementation, is the component of the system that performs the evaluation of the design. The collection of data takes place over two separate

topologies and is the result of a variety of experiments. The findings demonstrate that the system is behaving properly, that it is carrying out its duties as designed, and that it is producing intriguing findings. In addition, the contrast between a flooding system and an ant-based design reveals that the latter produces a more successful end in terms of the amount of material recovered as well as the length of the route. The contribution made by this research is to provide an alternative to the routing approaches that are presently being used in the NDN area that has the potential to produce positive outcomes. With any luck, the proposed solution will be able to provide support to more effort in this area of study.



## CHAPTER 3. RELATED WORK

This investigation began off as a Specialization Project, during which a literature research on NDN, ant colony, and Swarm Intelligence and their corresponding classes was carried out. The results of this review can be found in Section 2.1, Section 2.2, and Section 2.3 accordingly. As a result, this was the context when we first started working on this project and made the choice to use Name Data Networking as an ant-based solution for the SI. Beginning from this juncture, the operation that was carried out will be detailed throughout the remainder of this section, and it will be shown graphically in Figure 3.1. The primary purpose of this research was to investigate whether or not it would be possible to implement a Swarm strategy on the routing layer of a Named Data Network.

Following the completion of this study, there was a general understanding of ant colonies and SI; but, in order to deal with them, a more in-depth knowledge of the NDN and the system based on ants was necessary. Section 1.2 posed two primary research topics with this objective in mind. Because these ideas serve as the framework upon which this investigation is based, Section 2 contains the in-depth research that was conducted on these topics.

The first RQ examines the feasibility of using a SI approach to routing in NDN, while the second investigates the system's scalability and performance in the routing and forwarding planes. An integrative theoretical design of SI and NDN principles is offered as a potential solution to the RQs, after designing, simulation implemented for investigating the behavior and their performance. The tests use a genuine backbone

network architecture, as described in the simulation section, to examine the scalability and performance of the developed system.



Figure 3.1. Methodology Flow.

As can be seen in Figure 3.1, the stages of Design and Implementation are separated by a number of iterations in between them. This is due to the fact that the design is intimately connected to the manner in which the system should be executed, and as a result, throughout the process of implementation, design are discovered and made. In addition, both the design and the implementation began with basic routing, but as the iterations progressed, the complexity of the system expanded.

The goals, data points, and outcomes are all laid out in detail for each experiment. This assessment makes use of non-traditional methods. Qualitative methods have been utilized to analyze the outcomes persistently via the use of raw data and events collection to demonstrate the right operation of the systems and the established architecture. However, a quantitative strategy has been taken to investigate the system's reliability, scalability, and overall performance. A variety of statistical techniques are used to data acquired by running several simulations. There are three primary approaches that were used: highest value achieved through simulations, the average parameters, and a confidence interval that is 95% larger than this average value. When dealing with tables, the maximum is used to examine the worst-case scenario, which reveals the required resources in order to implement the design that is offered. The typical measurement, which considers both the amount of time spent retrieving material and the content itself, is used to provide an estimate of the value that may be anticipated. Despite the fact that it is essential to provide this figure together with the confidence interval for 95%, which quantifies the degree of unpredictability associated with the sampling procedure.

Each experiment describes its goals, the information that will be gathered, and the findings that will be evaluated. Several different strategies have been used in the

course of this assessment. An approach that is qualitative has been utilized for the purpose of demonstrating the correct systems related to routing and forwarding, as well implementation of architecture. This has been accomplished by carefully analyzing the results while collecting raw data and events. While a quantitative technique was used to investigate the system's consistency, scalability, and general performance in order to explore these aspects. Statistical approaches are used to the analysis of the accumulated data from the various simulations. The greatest values that could be achieved via the simulations, the average parameter, and a confidence interval centered on this average value were the three primary strategies that were implemented. When interacting with tables, the maximum is utilized to examine the worst-case situation, which reveals the required resources to employ the provided design. It is helpful to get a sense of the value that can be anticipated by using the average measurement, which is performed across all of the content and retrieval periods. Despite the fact that it is essential to provide this figure with the confidence interval for 95%, which quantifies the degree of unpredictability associated with the sampling procedure.

It is possible that using a home-made network simulator may give rise to certain problems. Because of the necessity for flexibility and freedom in order to create and execute the necessary system, this option was made. It would have been possible to conduct comparison studies with other software, such as NLSR, if a popular simulator like NS-3 had been used. NS-3 includes its own NDN model.

## **3.1 Model Parameters**

In the system model, various parameters are crucial for simulating the behavior of the network accurately. Here are the key model parameters:

### **3.1.1 Topology Configuration**

- **Number of Computers (Nodes):** This parameter defines the total number of nodes or computers in the network. It determines the scale and complexity of the simulated network. In this model 5 computers were used.

- **Number of Routers:** Specifies the quantity of routers strategically positioned within the network to manage packet forwarding and routing decisions.
- **Link Types and Properties:** Describes the characteristics of links between nodes, including bandwidth, latency, reliability, and other properties affecting data transmission.

### **3.1.2 Traffic Characteristics**

- **Packet Sending Frequency:** Determines how frequently packets are generated and transmitted within the network. It influences traffic load and dynamics. The frequency at which packets are sent can be determined based on the flow data rates and the number of sender-sink agents. With flow data rates ranging from 1Mbps to 3Mbps and considering 2 to 8 sender-sink agents, the packet sending frequency may vary accordingly. Higher flow data rates and more sender-sink agents would result in more frequent packet transmissions.
- **Packet Length:** Specifies the size of data packets transmitted across the network. It impacts bandwidth utilization and network performance. The length of packets transmitted across the network is not explicitly specified in the provided parameters. However, it can typically range from a few bytes to several kilobytes or megabytes, depending on the application and data being transmitted. The length of packets can affect the efficiency of data transmission, with larger packets potentially consuming more bandwidth but carrying more data per transmission.

### **3.1.3 Bandwidth of Links**

- The bandwidth of links within the network varies based on the type of link and its purpose. The bottleneck bandwidth, ranging from 2Mbps to 8Mbps, represents the maximum data transfer rate for bottleneck links in the network. Access links have a higher bandwidth of 1000Mbps, providing faster data transmission between nodes and access points. Bandwidth allocation impacts the speed and efficiency of data transmission, with higher bandwidth links supporting faster communication and potentially reducing congestion.

### **3.1.4 Other Considerations**

- The access delay, set at 0.1ms, represents the delay experienced in accessing data from nodes within the network. The bottleneck delay, set at 5ms, represents the delay experienced in data transmission through bottleneck links. Simulation duration is set to 60 seconds, allowing for observation of network behavior over a specified period.

### **3.1.5 Type of Traffic**

- The authors suggested using the Constant Bit Rate (CBR) traffic model. In CBR traffic, data packets are transmitted at a constant rate. This type of traffic pattern is often used to model applications with consistent data transmission requirements, such as real-time multimedia streaming or voice-over-IP (VoIP) services.

### **3.1.6 Simulation Environment**

- **Simulation Duration:** Sets the duration of each simulation run, allowing observation of network behavior over time.
- **Simulation Framework:** Specifies the software platform or framework used for simulation, such as custom-built simulators or established simulation tools like NS-3 or OMNeT++.
- **Experiment Design:** Outlines the specific experiments conducted to evaluate the performance of the network under various conditions and scenarios.
- **Routing Algorithm:** Describes the algorithm or strategy used for routing packets within the network, such as traditional routing protocols or novel approaches like Swarm Intelligence.
- **Forwarding Scheme:** Specifies how packets are forwarded from source to destination, considering factors like packet priority, routing table management, and congestion control.

## **CHAPTER 4. SIMULATION PROGRAM**

This chapter explains the ant colony optimization (ACO) routing algorithm, and how it is used in the framework of named domain networking (NDN). The implementation of ACO in the ndnSIM platform is described in the next chapter. Details simulation parameters are also given in this chapter. Finally, the topologies used to evaluate the simulation are described in this chapter.

### **4.1 Design**

Ant colony optimization has been shown to be a useful swarm optimization algorithm for routing in a network. This section describes both architectural level design and application level design for the routing algorithm. Architectural level changes are the changes that need to be made to packet structure, and the different tables used in NDN in order to implement the ACO algorithm. Application level design includes changes made to the implementation of the routing algorithm in ns-3 in order to implement the swarm method.

#### **4.1.1 Architecture level**

Swarm Intelligence integration into a Named Data Networking topology begins with architecture. The table and packet levels are where the majority of the most significant modifications are made when using Zhang et al. [1]'s presentation of the existing architecture of the NDN. These changes will not have an effect on the

fundamental idea behind ICN, but they will make it possible to include a variety of alternative routing strategies.

Typical NDN routing, has been described in Chapter 2. The Consumer node starts the process of communication by sending an Interest packet, which is a request for a specific Data that is requested. Any node which receives the Interest packet will check to see if the information is in its own Content Store (CS). If the data is not in the CS, and it is not in the Pending Interest Table (PIT) for this node, then the Interest packet is forwarded on. If the information is not in the CS but is in its PIT, the interface that the Interest packet was received from is added to the list of requests for data. If the data is in the CS, it is sent along the same route on which it was received back to the Consumer.

#### **4.1.1.1 Packets**

Wang et al. [101] created the Hello packet, a subset of the Interest and Data packet that aids in neighbor detection and promotion. This packet is used by every node in the network to check up on its neighbors' health. The packet is small because it contains just the data a router needs to identify its immediate surroundings and operational status. Similarly, in this work the ant packets are introduced which deposit pheromones and create paths through the network.

The design of the routing algorithm for NDN generally uses two different types of packets: interest packets and data packets. Additional two new packet types have been introduced in order to accommodate swarm routing inside this scheme. There are a total of four distinct types, each exhibiting distinctive characteristics and habits. These packet types are summarized in Table 4.1.

The control plane is traversed via light-weight packets known as Ants. Their primary responsibility is to alter the network's routing data. The packet's forward ant is an Ant Interest Packet that specifies the originator node ID, name of data requested with a nonce, pheromone value that is its destination, its expected lifespan in hops, and a nonce. The nonce or random term helps to uniquely identify the request and prevent multiple requests from traversing the network causing unnecessary congestion. The Ant Interest packets travel the network to find the location of their target data. Once

the Ant Interest packet reaches the data it is looking for, the node where the data is located will generate an Ant Domain packet, if it has not yet generated one.

Table 4.1 Packet types.

No	Packet type	Packet Function	Fields
1	Ant Interest Packet (forward ant)	Generated to create paths to data that may be used by the node, akin to caching in the network.	Originator Node ID, Name of Data Requested and Nonce, Pheromone Value, Lifespan, Path History= {}
2	Ant Domain Packet (backward ant)	Carry pheromone information back towards the data source after an Ant Interest packet reaches the content or times out.	Name of Data Object, Provider Node ID, Pheromone Value, Lifespan, Path History
3	Interest Packet	Created by Consumer Node to request access to a specific object.	Originator Node ID, Name of Data Requested and Nonce, Lifespan, Path History= {}
4	Data Content Packet	Carries requested data back to the Consumer node along the best path guided by pheromones.	Name of Data Object, Lifespan

The Ant Domain packets update the pheromone trail from the Producer node back to the Consumer node by following backwards the path of the Ant Interest. It is lightweight and compact, and it uses the control plane to perform routing functions. The key difference between the Ant Interest and the Ant Domain is that the Ant Interest packet contains the content being sought while the Ant Domain contains the domain name which has that content. Customers and nodes alike may utilize this information to get the routing phase ready to go by identifying and registering known domains.

The Interest packets and Data Content packets work similarly as for the original protocol. The Interest is the most frequent kind of packet used by NDN. It needs to describe the originator node, the name of the data requested and a random nonce to identify the request and prevent duplicate deliveries, a lifespan after which the data is

not useful. It will also keep track of the path it took in its path history. Its purpose is to convey a demand for certain material from a Producer node. The requested information together with its content name are both included in the answer packet, which is referred to as a Data Content Packet or Data Packet.

Other than their characteristics, the most noteworthy modification is the addition of priority with regard to packet class. In this architecture, priority is given to the packets carrying the actual content, while the other packets pass quietly beneath the control plane. Because of this, content packets (both Interest and Data) are prioritized above all others, even if they arrive later in time. In this way Ant Domain packets can use as much bandwidth as possible without negatively impacting content distribution and retrieval.

#### **4.1.1.2 Forward Information Base**

Each content name stored in the NDN FIB is associated with one or more interfaces, and the FIB also stores a metric evaluating the quality of the route associated with each interface. Examples of such metrics include Round Trip Delay Time (RTT), hop count, and channel bandwidth. We can build a swarm routing solution on top of this FIB architecture by maintaining, within the metric entry, the amount of pheromone associated with each interface-name pair. The pheromone concentration can serve as a proxy for the concentration of the target drug, indicating areas with the highest probability of containing it. High pheromone levels on multiple interfaces may suggest that the given content is available in multiple locations or that multiple redundant paths exist to the same location.

#### **4.1.1.3 Pending Interest Table and Pending Agent Table**

Diverse Interest and Data packets simplify learning and adapting to new topologies. In this context, NDN's forward agents are represented by Interest packets and NDN's backward agents by Data packets. While the Interest packets are in transit, the sender and receiver's names and interfaces are added to the Pending Interest Table. The node uses this table to keep track of requesting nodes and when the data packet is received matching the entry in the PIT, it sends the data packet back in the opposite direction towards the requesting node.

This data packet utilizes the PIT to backtrack along the forward ant's journey, all the while updating the FIB table with the new destination, the new interface used to get there, and the new pheromone concentration. Despite their similarity to the content of Interest and Data packets, the packets themselves are unique in their usage as forward and reverse agents. Thus, it is more efficient to use two distinct tables, one for the content retrieval and another for the swarm routing system, rather as a single PIT table for both classes. This measure is chosen because of the similarity in the distribution of the rows and columns in both tables. When an Interest comes, the PIT makes a new record, but if the Interest already exists under a different name, it simply updates the entry with the incoming interface. For each new Ant Interest that is received, a new entry is made in the PAT. It is also worth noting that, in practice, these two tables might be integrated in a way that is compatible with the current NDN architecture, therefore optimizing packet processing by moving it from the application layer to the physical layer.

## **4.1.2 Application level**

The NDN network makes it possible for any kind of algorithm to be used with it when it comes to the control plane task of routing. Other systems not using NDN can also perform routing on this architecture. There are no restrictions. In order to communicate and retrieve data, Interest and Data packets must be used. If the node has a routing algorithm, it may utilize the Content Store to cache previously sent interest packets, keep track of them in the Pending Interest Table, and update the Forward Information Base with its findings. While supplemental structures to aid routing are acceptable, they must never be used in place of the main NDN structure.

### **4.1.2.1 Routing-forwarding strategy**

There will also be a separation in the routing technique used for control packets and content packets. Even though they use the same basis for packet routing, the function's insights will vary. This is due to the fact that the criteria for the control plane are distinctive from those of the forwarding plane. It is necessary for the material to be obtained in a quick and reliable manner despite the fact that the ants have to work simultaneously to attempt to find the best route while also providing other routes.

Thus, the ants and content packets will follow stochastic strategies that promote the best path known at the moment rather than converge to the optimal one. A heuristic role in the decision making process is reflected in the stochastic nature of the approach in both scenarios. In this approach, the path the packets take to their final resting place is not predetermined, and the packets may take any route to get there. The Interest tables function differently, which is another distinction. The PIT will receive and send Interests and keep the data associated with them. In addition, the table will save all Interest with the same name but will not transmit any duplicates. However, when an ant Interest is received by the PAT, it is transmitted together with the relevant data and stored.

In this scenario, Interest packets from the same ant colony that arrive one after the other will likewise be transmitted. This variation in behavior is an effort to enhance pheromone laying along travel routes and maximize efficiency in content retrieval. Because the NDN design permits in-network storage, i.e. caching, there may be material on a node that deviates from the best route, making the stochastic approach of content routing all the more crucial. The non-deterministic discovery of a content-related other route is therefore intriguing.

#### **4.1.2.2 Routing process**

The Consumer is in charge of producing the Interest packets' ant and content. Figure 4.2 describes how a piece of information is sent, sent, and retrieved. Initiating the retrieval process, the Consumer creates Interest packets that contain the name of the content and sends them to the closest node. The router receives an Interest packet over an incoming interface and processes it. The ID, name, and incoming interface of the packet are documented in the Port Address Translation (PAT) table of the Interest. Subsequently, the Forward Engine ascertains the appropriate outgoing interface for the packet's transmission, and the node proceeds to do this. If the interface is part of a router, processing continues as described above; otherwise, the message has been sent to the Producer.

When this occurs, the Producer tries to see whether it already has the requested material. In this case, it sends an ant Data packet with c's name to the same edge node. A node checks the PAT table to see whether an ant's data packet matches. Under these

circumstances, the router will look for the destination name in the FIB record. If the router finds such a record, it changes the incoming interface and pheromone amount data; otherwise, it produces the record. From the PAT entry, it obtains the incoming interface of the Interest, and then it transmits the Ant Data via that interface. When the Ant Data reaches the Consumer, the Consumer is aware that there is a route in the network via which it is possible to receive the real content. As a result, it is now able to transmit a content Interest in order to collect the data object that it requires.

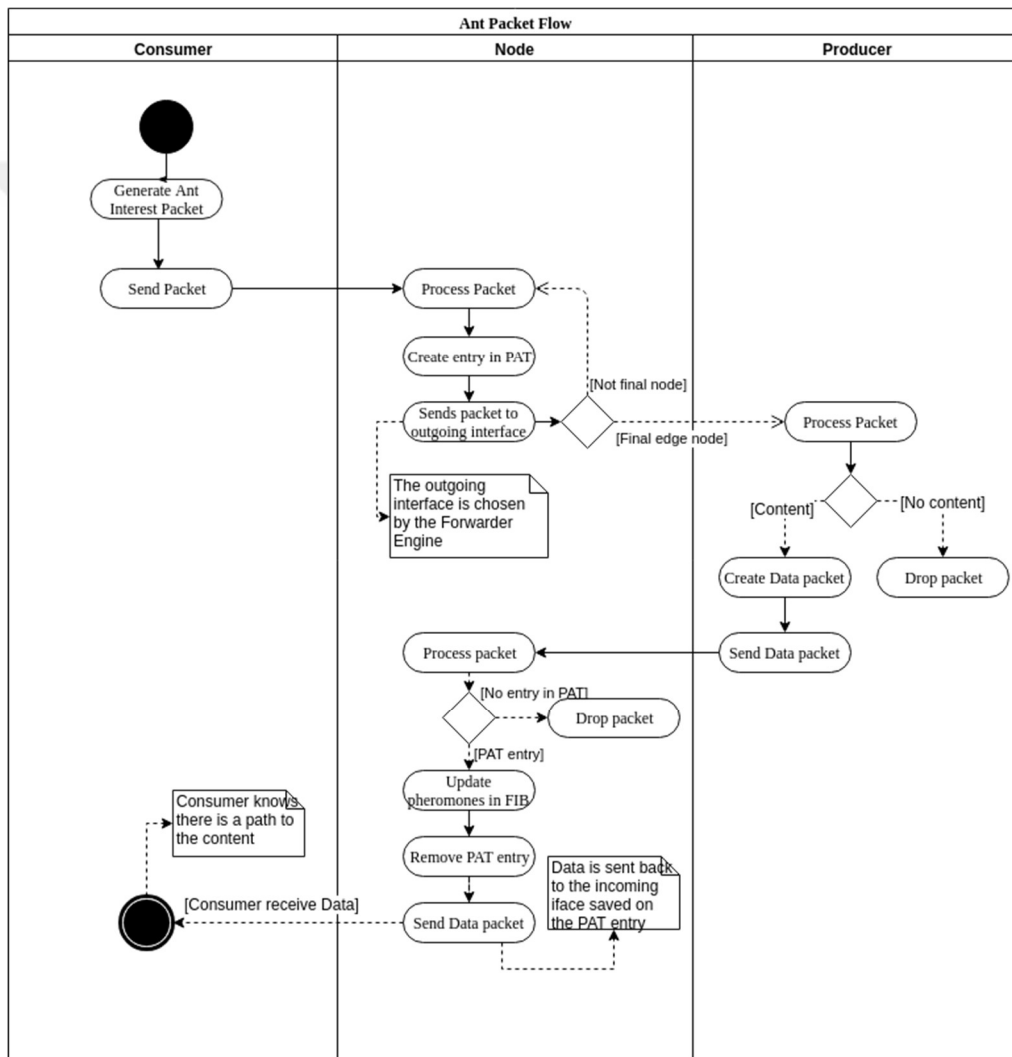


Figure 4.1. Routing packet flow of ant packets [100].

After some time has passed, the requested material is sent to the Consumer. Figure 4.2 illustrates the approach that will be followed. Figure 4.1 shows ants completing the route in the first stage. A blast of ants is sent. Ten ants will leave one millisecond apart and roam the network concurrently. After an Ant finds the data, the

Consumer may request it. After then, the procedure shown in Figure 4.2 gets underway.

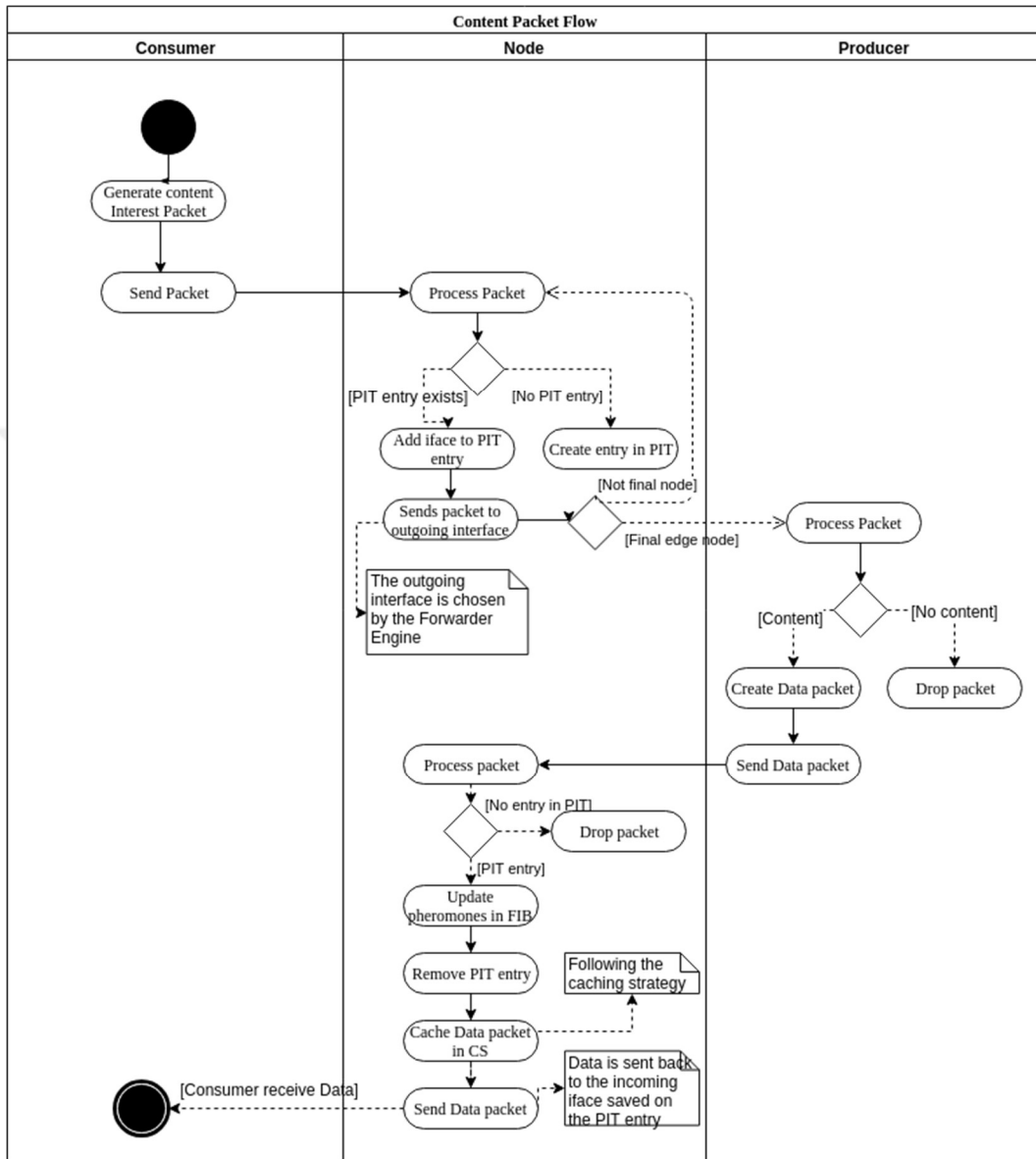


Figure 4.2. Routing packet flow of content packets [100].

## 4.2 Implementation

This section described the implementation of the algorithm. The implementation is written in Python and C++ language. The platform is Ubuntu 20.04 on Oracle Virtualbox, using the ndnSIM 2.0 [102] program. ndnSIM is a simulator for named domain networking systems, based in the popular ns-3 simulator. Ns-3 [11] is a well-

known simulation platform for simulation of different types of networks. The system includes implementations of all OSI layers, and many different types of networks can be modeled using this platform.

The implementation of NDN is provided by ndnSIM. ndnSIM provides a discrete event simulator with libraries for queue and time management. The ndnSIM program is based on an older version of ns-3, has essentially been forked for development. ns-3 has been in development since the early 2000s, and it follows ns-2 which was in use before then. The ndnSIM platform was first released in 2012. There has been a lot of work on the platform, and it is known to be robust and accurate, used in many different projects. The goal of this work was to add a new routing algorithm based on ACO to ndnSIM.

### **4.2.1 Packet**

Both ant-based and content-based interests and data are included inside the Packet, which acts as a container for them. It holds content and routing and forwarding information. The NDN architectural design determines its unique Nonce; this Nonce is the essential component in preventing loops in the network.

### **4.2.2 Interface**

The Interface module routes network traffic. Sending each packet takes proportional to the bandwidth that has been allocated to the interface. It also provides a queue for the packets that have been received and are waiting to be sent.

### **4.2.3 Consumer**

This component makes network requests for content via its single Interface. There are two anticipated processes: To begin, if the requested content name is a match, then the data object is received. In the event that the given name does not correspond to an existing item, a data object with meta-data describing the actual content will be returned.

## 4.2.4 Producer

To help disperse data objects with specific content names, this module provides a distribution mechanism. If the data requested already exists, it will be retrieved. Data is instead constructed with the meta-data already filled in with the names of the current content, using the longest name prefix matching approach. This takes use of the hierarchical nature of the naming system and the easily accessible domains.

## 4.2.5 Node

In a network, the node is the fundamental unit. This design incorporates a Content Store, an Interface or Interfaces, a FIB, a PIT, and a PAT table. It handles the routing and forwarding operations and may use many approaches based on the same infrastructure.

## 4.2.6 Helper Modules

ndnSIM contains a class of objects known as helpers. StackHelper class is used to install the NDN protocol stack on nodes, giving them all the data components and methods needed to perform NDN network simulation. The RoutingHelper class is extended for NDN in order to set up and maintain routes simply in the network. In this work the RoutingHelper is not used, as ACO is handling the routing. ApplicationHelper allows the creation of applications for Consumer and Producer nodes which can generate Interest packets according to some rule, or respond in a given way when receiving an Interest packet for which data which they have. There is also a class LinkControlHelper and ndnHelper which allows the programmer to model changes to the Content Store behavior at nodes.

FibHelper class is used to add routes directly to the Fib tables of nodes on a route. This is useful in first establishing routes for the ACO algorithm.

The main component that of the ACO algorithm was implemented by extending the class Strategy. The strategy class determines the strategy for determining the next link in the network when an interest packet or a data packet is received. Within ndnSIM there is an implementation of a Multicast routing protocol and a BestRoute protocol

which prefers the route with the lowest cost. The Multicast routing protocol was used as a model for distributing Ant packets. Figure 4.3, Figure 4.4 and Figure 4.5 show the chosen topologies. ndnSIM allows the programmer to follow every step of the routing process and thoroughly analyze each simulated occurrence.

### 4.3 Experiments

The descriptions of major parameters of the simulation are described in Table 4.2.

Table 4.2 Variable descriptions.

<b>Variable</b>	<b>Definition</b>
<b>Ant generating rate</b>	The rate at which ants are produced and distributed.
<b>Ants per request</b>	The total number of ants that were sent before a request was made for the material.
<b>Maximum pheromone laid</b>	The total amount of pheromone that was left behind by each of the backward agents.
<b>Pheromone reduction</b>	The constant that the evaporation mechanism uses to bring the quantity of pheromone remaining in the interfaces down to a more manageable level.
<b>Evaporation rate</b>	It is necessary to ascertain the pace at which the pheromone must be reduced.
<b>Pheromone reinforcement power</b>	Pheromone enhancement value that may be employed. Variables: Ant, Content or Domain For this work, the pheromone power is fixed regardless of the value of variables.
<b>Packet lifetime</b>	Time To Live, as measured in the number of hops, for the packets.
<b>FIB table timeout</b>	The amount of time that passes before an entry in the FIB table gets removed. For this simulation FIB table entries remain constant for the duration of the simulation.
<b>Seed</b>	The seed that was utilized for the simulation.

Values for these parameters, when they are relevant, are given in summary form in Table 4.3. These parameters were found experimentally to give good results for these simulations. More detailed analysis of values will be for future work.

Table 4.3 Variable values.

<b>Variable</b>	<b>Scenario 1 and Scenario 3</b>	<b>Scenario 2</b>
<b>Ant generating rate</b>	50 packets/second.	5 packets/second.
<b>Ants per request</b>	5 data packets/1 ant packet.	
<b>Maximum pheromone laid</b>	500	
<b>Evaporation rate</b>	0.5 seconds	5 seconds
<b>Pheromone reinforce power</b>	1	1
<b>Packet size</b>	256	
<b>Packet lifetime</b>	4 seconds.	
<b>Seed</b>	0	

There are three scenarios investigated in this work. The network parameters are listed in Table 4.4. Each scenario is described with further detail in the next section.

Table 4.4 Network and traffic variable values.

<b>Parameter</b>	<b>Scenario 1 and Scenario 3</b>	<b>Scenario 2</b>
<b>Ant Interest Packet Generation Rate</b>	50 packets per second	5 packets per second
<b>Data Interest Packet Generation Rate</b>	10 packets per second.	1 packet per second.
<b>Simulation Duration</b>	20 seconds	200 seconds.
<b>Ant Domain Packet Size</b>	256 bytes	
<b>Data Packet Size</b>	1024 bytes	

<b>Bandwidth</b>	1Mbps between network nodes.
<b>Access Bandwidth</b>	10Mbps from consumer to first node and from producer to first node in the network.
<b>Delay</b>	1ms to 20ms for network nodes
<b>Access Delay</b>	50ms from consumer to first node in the network.

Experiments conducted as part of this study are shown here with explanations. Every one of them concentrates on certain objectives that aim to validate the conduct that is anticipated. Due to the fact that each operation has a unique set of goals, the information that is acquired will likewise be unique. The experiments are given in an order that increases in complexity in terms of how they were implemented and the goals they sought to achieve.

Table 4.5 Summary of experiments.

<b>Experiment No</b>	<b>Topology</b>	<b>Num. Consumers</b>	<b>Num. Producers</b>	<b>Content Names</b>	<b>Simulations</b>
<b>1</b>	Simple	1	1	2	1
<b>2</b>	Simple	2	1	3	1
<b>3</b>	Simple	2	1	3	1

The aforementioned trials may be broken down into two primary categories of outcomes. For each scenario, the rate of generation of ant interest packets is constant across time. Two different types of data traffic are considered: constant bit rate arrival and exponentially distributed packet arrivals.

### 4.3.1 Scenario 1

Verifying the implementation's basic routing ideas and needs is the main goal of this scenario. This scenario anticipates obtaining compelling results of the proper functioning of the routing system by using a variety of executions aimed at achieving a variety of objectives. During the testing phase, an incremental approach is used, and

the level of complexity steadily rises with each iteration. Figure 4.3 displays the topology that was applied to the problem. Table 4.6 gives the link parameters investigated in this scenario.

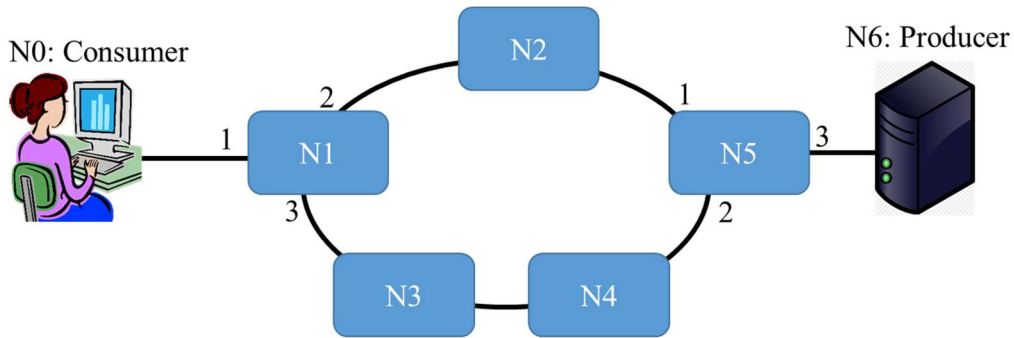


Figure 4.3. Scenario 1: One consumer, one producer network topology.

Table 4.6 Link Parameters for Scenario 1.

Link	Capacity	Delay	Max. Packets
N0 (Consumer) – N1	10 Mbps	50 ms	200
N1 – N2	1 Mbps	20 ms	20
N2 – N5	1 Mbps	20 ms	20
N1 – N3	1 Mbps	20 ms	20
N3 – N4	1 Mbps	1 ms	20
N4 – N5	1 Mbps	1 ms	20
N5 – N6 (Producer)	10 Mbps	1 ms	200

The values shown in Table 4.3 are going to be used for all of the variables in this scenario. In the restrictions field of each experiment, it is specified whether the experiment may diverge from the information shown in this table.

The primary purpose of this scenario is to put the fundamental routing concepts and needs in the implementation to the test (Table 4.4). Because of this, just ant packets are used, and the content itself is not sought. This choice is the result of coming to the

realization that it is necessary to put in place an accurate routing system in order to be able to access content objects.

Table 4.7 Scenario 1: Ant behavior in the system.

<b>Experiment 1</b>	<b>Investigation of the activities of ants inside the system.</b>
<b>Description</b>	A Consumer C1 (Node 0) requests information which is at Producer P1 (Node 6). The consumer first sends Ant Interest packets through the network, then sends Interest packets to obtain this data.
<b>Components</b>	One consumer and one producer.
<b>Constraints</b>	Figure 4.3 depicts the topology, Table 4.6 gives parameters of links. Table 4.3 and Table 4.4 summarize other parameters.
<b>Objective</b>	<p>This experiment is designed to confirm that each module is functioning correctly, with a focus on:</p> <ul style="list-style-type: none"> <li>• Determining whether or not the ants successfully accomplish the task of depositing pheromones along the better path for data.</li> <li>• Determining whether or not the ants successfully accomplish the task of route finding.</li> <li>• Verify the method by which the information in the tables of the node is populated</li> </ul>
<b>Data Gathered</b>	The packet delay, and packet drop rate are examined to analyze the performance of the scenario. The number of pheromones on each link is also analyzed to see whether the algorithm converges correctly to prefer the upper path through the network which incurs less delay. The simulator is run in debug mode, and debugging printouts are collected from the Consumer, the Receiver and the ACO routing algorithm so that all of the events may be analyzed separately.

<b>Expected Result</b>	<p>Ant Domain packets should follow backwards the path taken by Ant Interest packets, with nodes on the backward path adding pheromones in the path towards the direction they receive the Ant Domain packet from.</p> <p>The resulting pheromone path should cause data packets to prefer the low latency path along the top C1-N1-N2-N5-P1 rather than the higher latency path C1-N1-N3-N4-N5-P1. The number of entries in the PIT and PAT tables should fluctuate over time as interest packets are sent.</p>
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### 4.3.2 Scenario 2

This section describes a scenario where there are two consumers and one producer. This turned out to be the most complicated scenario, as both consumers routed interest packets in both directions through the network. Both are accessing a resource on Node 6 which is the producer. The scenario is illustrated in Figure 4.4 and link parameters are given in Table 4.8. Because there are two consumers, each consumer generates its own Ant Interest packets, effectively doubling the interest packet traffic in the network. It is of interest to determine how this affects delay or rate of packet loss and whether path routing is improved with twice the number of ants in the network.

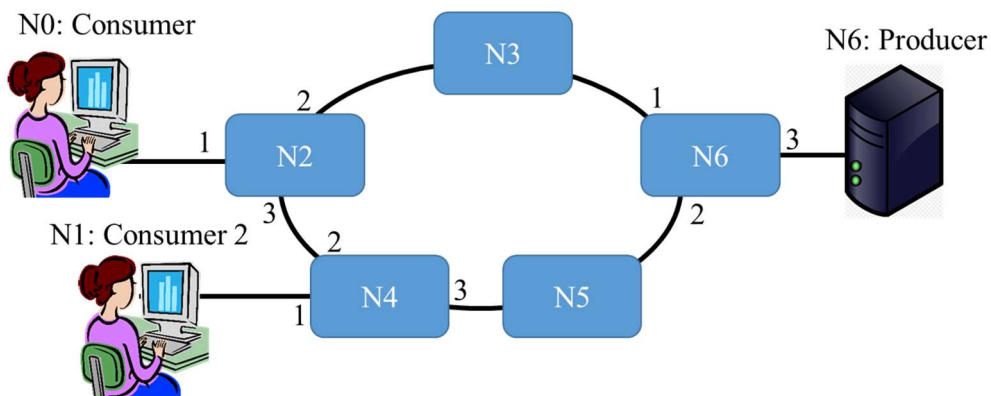


Figure 4.4. Two consumer network topology.

Table 4.8 Link Parameters for Scenario 2.

Link	Capacity	Delay	Max. Packets
N0 (Consumer 1) – N2	10 Mbps	50 ms	200
N1 (Consumer 2) – N4	10 Mbps	50 ms	200
N2 – N4	1 Mbps	20 ms	20
N4 – N5	1 Mbps	20 ms	20
N5 – N6	1 Mbps	20 ms	20
N2 – N3	1 Mbps	1 ms	20
N3 – N6	1 Mbps	1 ms	20
N6 – N7 (Producer)	10 Mbps	1 ms	200

A complication in this scenario was the issue of Content Store lookup. When traffic was high compared to the bandwidth of the channel, packets were significantly delayed and at times Content Store lookup did not work. To compensate for this the rate is reduced and the duration of the simulation is increased for this scenario, as shown in Table 4.3 and Table 4.4.

Table 4.9 Scenario 2: Synergy between consumers.

<b>Experiment 2</b>	<b>Analysis of customer relationships based on harmony.</b>
<b>Description</b>	Consumers C1 (Node 0) and C2 (Node 1) request information which is at Producer P1 (Node 7). The consumers first send Ant Interest packets through the network, then send Interest packets to obtain this data. Data requests start at 1 second for Consumer 1 and at the 2 seconds for Consumer 2.
<b>Components</b>	Two consumers, one provider.
<b>Constraints</b>	Figure 4.4 depicts the topology, Table 4.8 gives parameters of links. Table 4.3 and Table 4.4 summarize other parameters.
<b>Objective</b>	The aims are as follows:

	<ul style="list-style-type: none"> <li>• Does the presence of two customers speed up the route finding process?</li> <li>• Is the data requested by Consumer C2 routed over the shorter delay path, traversing Node N2 or does it follow the path with fewer links to P1?</li> </ul>
<b>Data Gathered</b>	As previously, the packet delay, and packet drop rate are examined to analyze the performance of the scenario. The number of pheromones on each link are also analyzed and debugging output is studied.
<b>Expected Result</b>	It is anticipated that evidence will be obtained to show that increasing the number of agents in a network benefits the routing system. When compared to the last experiment, the number of pheromones should increase more quickly on nodes which are on the path of both Consumers to the Producer.  The resulting pheromone path should cause N3 to prefer the lower latency path along the top C2-N3-N1-N2-N5-P1, rather than the higher latency path C2-N3-N4-N5-P1.

### 4.3.3 Scenario 3

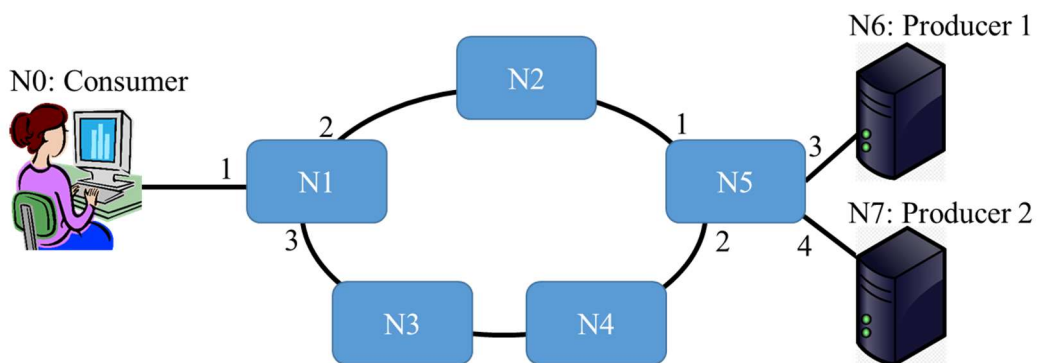


Figure 4.5. Two producer network topology.

Table 4.10 Link Parameters for Scenario 3.

Link	Capacity	Delay	Max. Packets
N0 (Consumer 1) – N1	10 Mbps	50 ms	200
N1 – N2	1 Mbps	1 ms	20
N2 – N5	1 Mbps	1 ms	20
N1 – N3	1 Mbps	20 ms	20
N3 – N4	1 Mbps	20 ms	20
N4 – N5	1 Mbps	20 ms	20
N5 – N6 (Producer 1)	10 Mbps	1 ms	200
N5 – N7 (Producer 2)	10 Mbps	1 ms	200

In this scenario there is a single consumer with two producers. The consumer produces Ant Interest packets and Interest packets separately for the resources at both Producers. Since both Producers are connected to the same network node, this scenario should also allow the route to be established more quickly.

Table 4.11 Scenario 3. Analysis of Data and in-network storage.

<b>Experiment 3</b>	<b>Examining Data Packets and Local Network Memory.</b>
<b>Description</b>	Consumer C1 (Node 0) requests information which is at Producer P1 (Node 6) and information which is at Producer P2 (Node 7). For data from both producers, consumer first sends Ant Interest packets through the network, then sends Interest packets to obtain this data. Data requests start at 1 second for data from Producer 1 and at the 2 seconds for data from Producer 2.
<b>Components</b>	One consumers, two providers.

<b>Constraints</b>	Figure 4.5 depicts the topology, Table 4.10 gives parameters of links. Table 4.3 and Table 4.4 summarize other parameters.
<b>Objective</b>	The goal of this scenario are to find if there is any change or error in routing due to having multiple types of packets in the system, and to see whether having multiple Ant Interest packets from the same customer for different resources also affects the establishment of routes.
<b>Data Gathered</b>	As previously, the packet delay, and packet drop rate are examined to analyze the performance of the scenario. The number of pheromones on each link are also analyzed and debugging output is studied.
<b>Expected Result</b>	It is expected that the two types of data are both correctly received, and the majority of traffic traverses the shorter latency path.

## **CHAPTER 5. RESULTS AND DISCUSSION**

This chapter presents the results of all scenarios. For each scenario, figures illustrating the results of the simulation are drawn and these results are analyzed. The obtained outcomes are compared to expected outcomes described in the previous chapter.

For each scenario, two different types of data traffic are considered. First constant bit rate (CBR) data traffic, then exponentially distributed data traffic is generated and the results are analyzed. CBR traffic is often used to model traffic such as file transfer and machine to machine communication links. Exponential distribution is more commonly used to model many browsing type activities. Video communication or streaming applications fall somewhere between these types. The number of bits per packet is fixed.

The data in this chapter was obtained from code written in ndnSIM. Results of simulations were written to text log file, and these were imported into Excel to analyze the results and produce plots.

### **5.1 Scenario 1**

Table 4.7 provides a detailed explanation of the scenario. Figure 5.1 shows the simulation running in the visualizer on ndnSIM, the figure was edited to show the node names and the latency on each link. Note that this mirrors the information in Figure 4.3 and Table 4.6. Other simulation and network parameters are as given in Table 4.3 and Table 4.4.

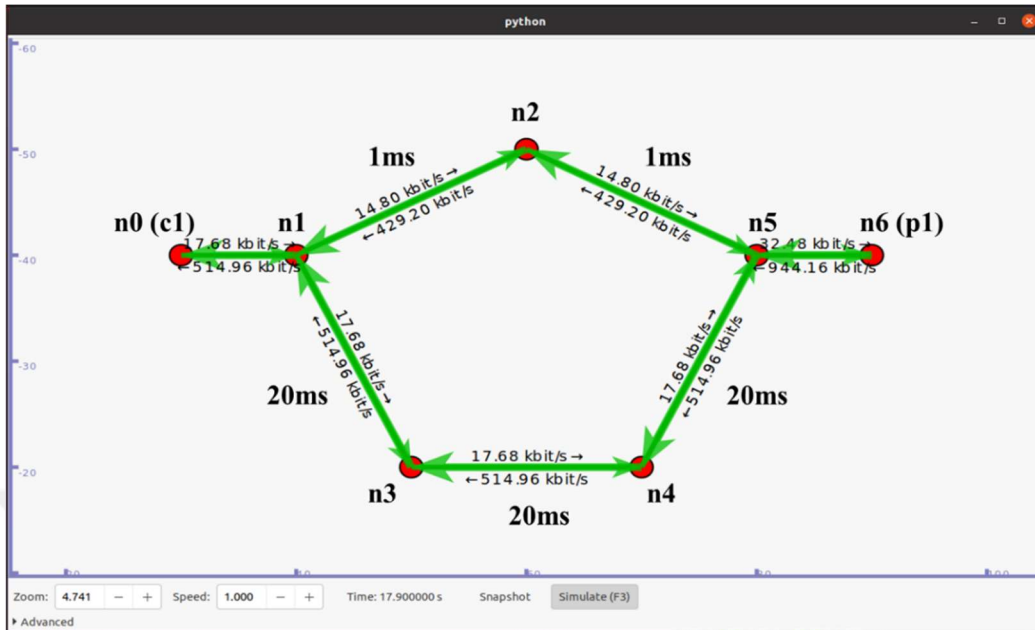


Figure 5.1. Scenario 1. Simulation in ndnSIM visualizer.

The progression of the pheromone is shown in Figure 5.2 to Figure 5.4. These figures were created based on traffic depicting Interest packets generated at a constant bit rate, with one Interest packet generated every 0.02 seconds (50 Interest packets per second).

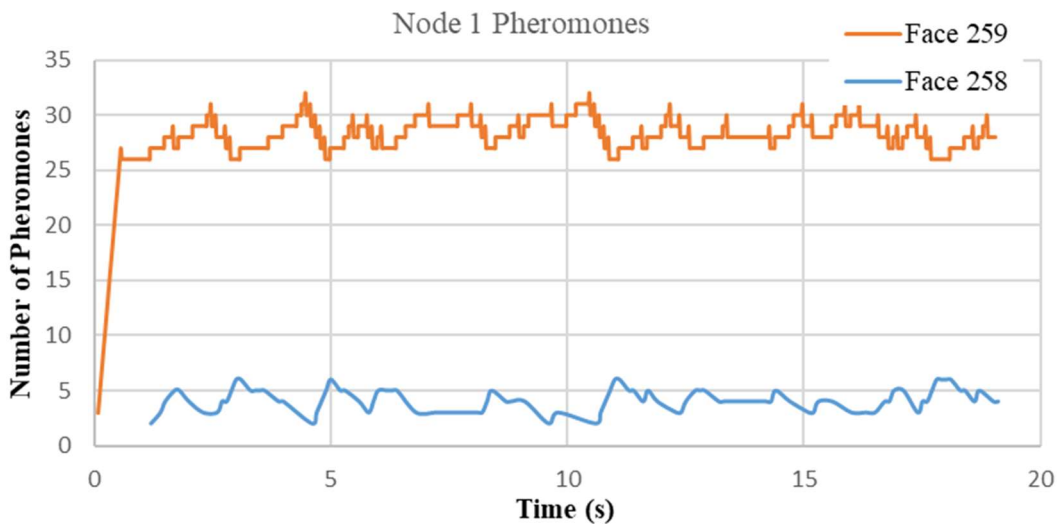


Figure 5.2. Scenario 1, Node 1 pheromone evolution in the faces for CBR traffic.

Pheromones are shown along the y-axis of the figures, while time is represented along the x-axis. Node 1 has two faces in this topology, one leading to node 2 and one

leading to node 3. These nodes both connect via different paths to node 5 and then to node 6 as can be seen in Figure 5.1. Thus the only node which makes a routing decision is Node 1. Below are the pheromones on Nodes 1 to 5. Node that ant packets are multicast through the network whereas data packets follow a path that is selected probabilistically based on the pheromones of the faces. So a data packet leaving Node 1, according to this is more likely to use Face 259 which leads to the faster route to the destination than to use Face 258.

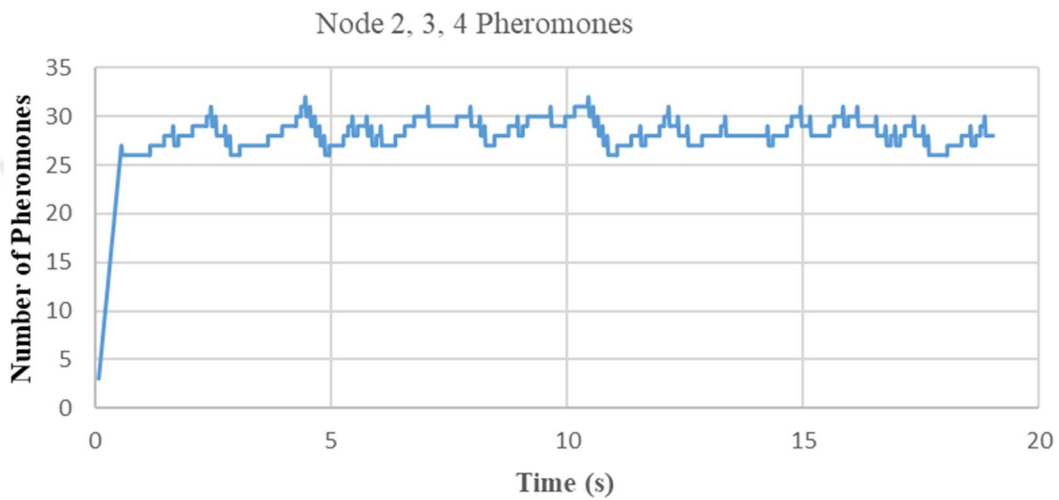


Figure 5.3. Scenario 1. Node 2 to Node 4 pheromone evolution in the nodes for CBR traffic.

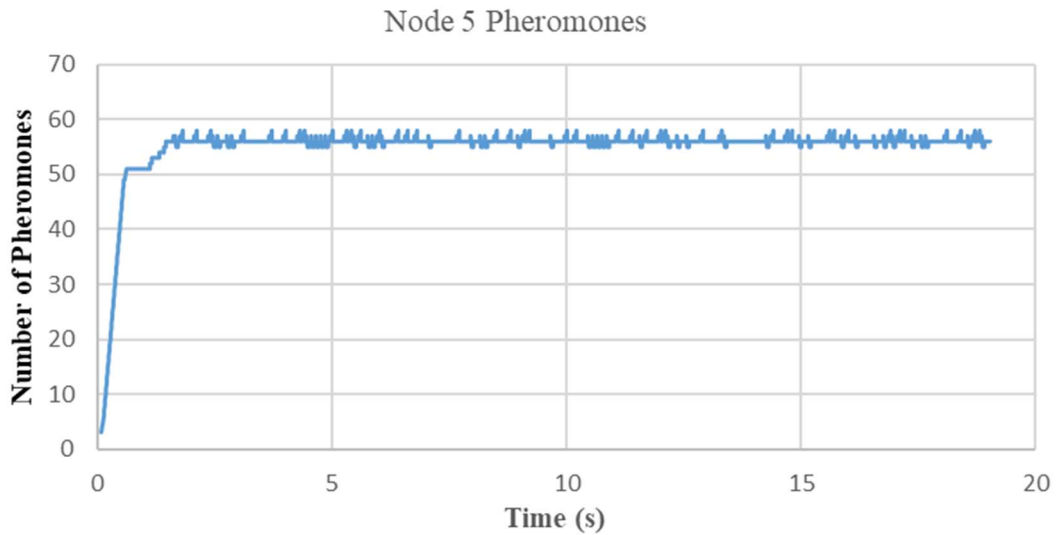


Figure 5.4. Scenario 1. Node 5 pheromone evolution in the node for CBR traffic.

Pheromone packets are multicast uniformly through the network, which means that Nodes 2 to 4 all receive the same Ant Interest packets. Since all packets arrive at these nodes and the nodes have only one outgoing link, the Ant Domain packets that

travel back down this path all leave the same amount of pheromones. These packets are then forwarded to Node 5, which as can be seen receives twice the volume of data that Node 1 transmits. In further work it is of interest to reduce the flooding caused by the multicast routing to reduce traffic load. No packet drops occurred in this topology with the volume of traffic generated, which was on average of 10 interest packets and 50 ant interest packets generated per second. Each interest packet was 1024 bytes while each ant interest packet was fixed at 256 bytes.

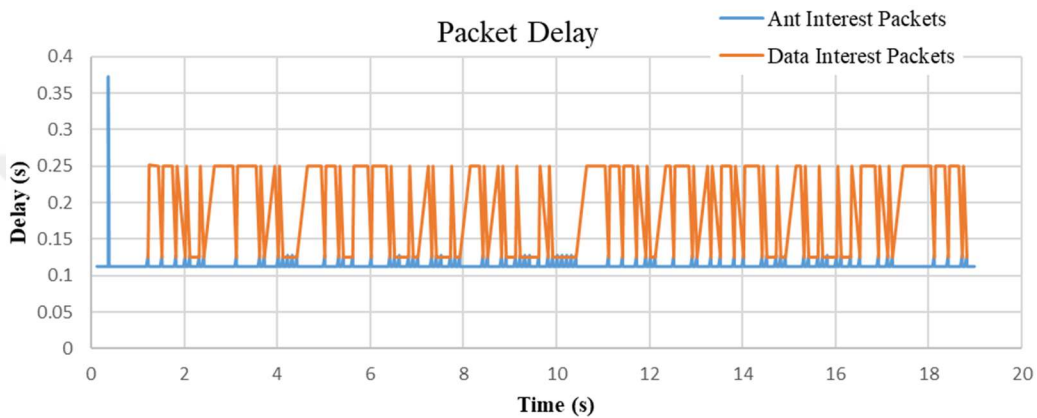


Figure 5.5. Scenario 1. Packet delay for CBR traffic.

Packet delay results in Figure 5.6 show that data packets are delayed more than ant packets. This occurs for two reasons. Firstly, ant packets are smaller than data packets, although the difference in delay due to this is not significant. The larger difference in delay is due to the fact that ant interest packets are flooded using the multicast protocol to all possible paths in the network. When an Ant Domain packet is produced in reply, it is always directed to the direction of the first received Ant Interest packet, thus the ant packet always takes the shorter path. Data packets on the other hand probabilistically pick one of the paths based on pheromones. Due to queuing in the network, this path chosen is occasionally the path with 20ms delay rather than the path with 1ms delay. This causes the delays shown in the data. While this may appear to be a waste for this simple scenario in more complicated scenarios with more simultaneous data transmissions it is important to spread the data traffic across alternative routes when necessary. This also provides robustness against changes in the topology of the network, as may occur due to mobility or other challenging conditions in wireless networks.

Next let us look at the pheromone evolution for exponentially arriving traffic on the same topology. Exponentially arriving interest packets are typical for internet browsing data. The bit length of a packet was fixed. Ant interest packets on the other hand were still transmitted at regular intervals.

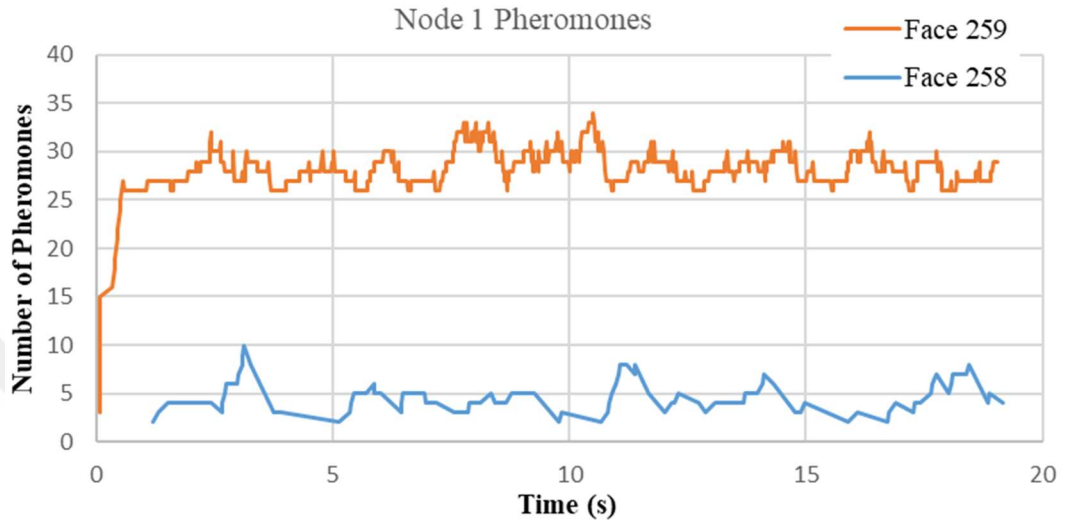


Figure 5.6. Scenario 1, Node 1 pheromone evolution in the faces for exponential traffic.

For exponential traffic, it is clear that the amount of pheromones varies slightly more over time. Although the ant interest packets are generated at a constant rate in both scenarios, the data packets being transmitted were randomly scheduled in the exponential case. Since data packets also leave pheromones, this led to a fluctuation in the amount of pheromones on each output face of the nodes. The average bit rate presented to the network is the same as for exponential traffic, and consequently in this scenario there are no packet drops.

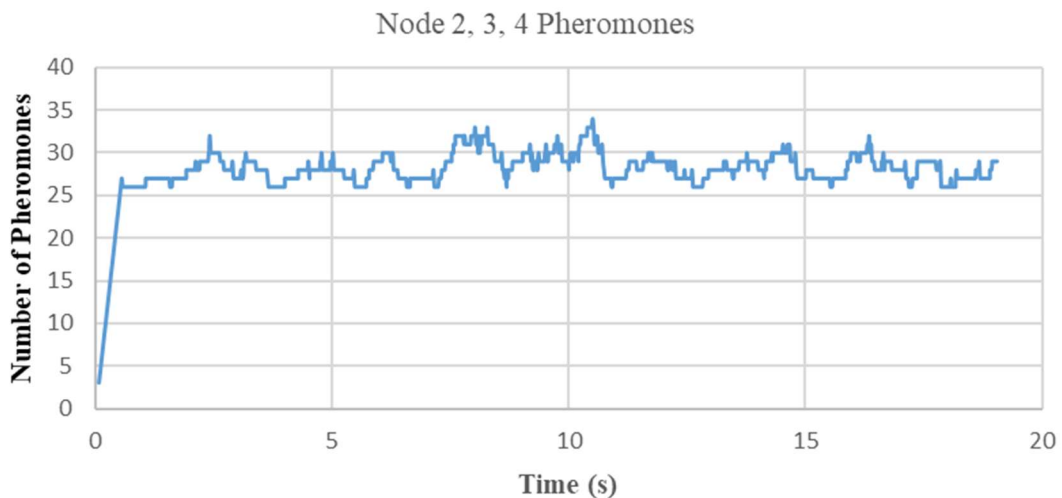


Figure 5.7. Scenario 1. Node 2 to Node 4 pheromone evolution in the nodes for exponential traffic.

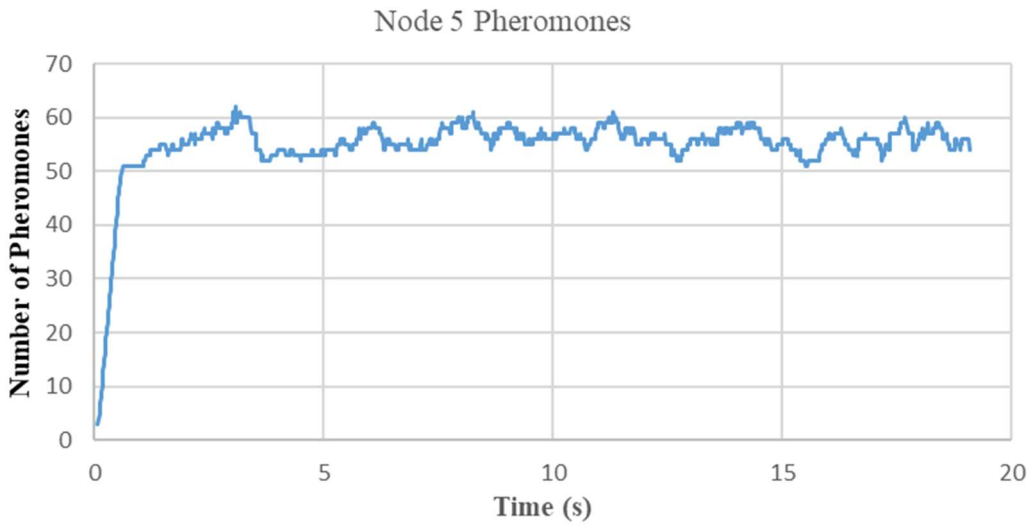


Figure 5.8. Scenario 1. Node 5 pheromone evolution in the node for exponential traffic.

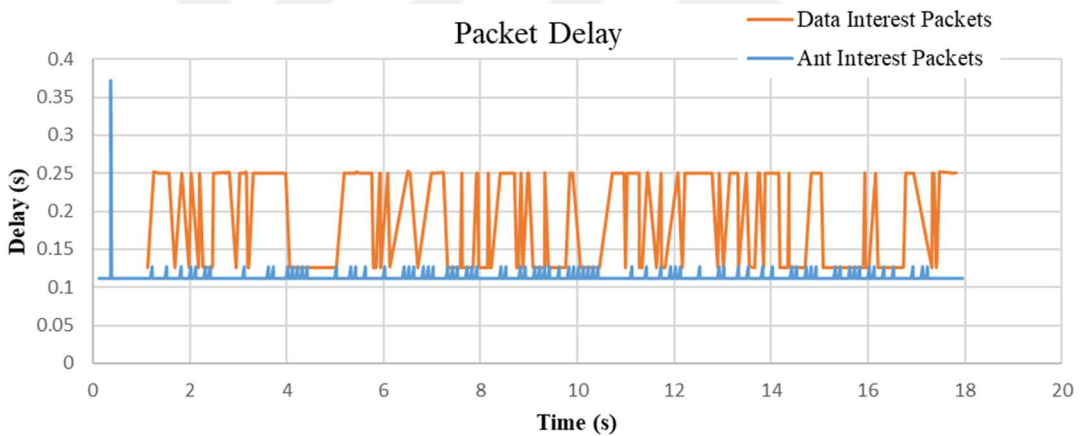


Figure 5.9. Scenario 1. Packet delay for exponential traffic.

In this simulation the pheromones listed in the PAT are set to expire within 500ms. This lifetime is adjustable within the code, however in the simulations that were performed with no mobility, it is shown to work successfully. The PAT keeps a record of the number of times a packet is successfully delivered back from a given neighbor of the node, indexed by the “face” that is used to communicate with that node. The results of every ant pheromone must be stored separately to allow the system to delete expired pheromones. This can be performed by ant “agents” in the system in a more advanced implementation, where ants can be small programs similar to viruses which can traverse the network. However, in this simulation the node routing strategy

keeps track of the PAT and all pheromones over time. Due to the small size of the network in these experiments, and the lack of mobility for the nodes, the network pheromone concentrations quickly converge. Decreasing the time it takes for the pheromone to expire would decrease the probability that a data node takes a less ideal path. It remains to be investigated in a high traffic system what result this will generate.

There are three key goals for this experiment: Determining whether or not the ants successfully accomplish the task of depositing pheromones along the better path for data, determining whether or not the ants successfully accomplish the task of route finding and verify the method by which the information in the tables of the node is populated. It is clear that tables are being correctly updates, as there are more pheromones along the lower latency path than along the higher latency path.

Not included in the aforementioned diagrams are the events created by the simulator that are used to assess the agents' forward and backward routes. These occurrences prove that the reversing agent travels in the same direction as the forward one did, therefore confirming that no loops were created during the discovery phase. In terms of the tables' functionality, the previously discussed relationship between PAT entries and pheromone levels provides strong evidence that nodes in the network act as predicted; this conclusion is corroborated by analyzing simulated events. As a consequence, the overall findings from this experiment are consistent with what was predicted beforehand (as shown in Table 4.4).

## **5.2 Scenario 2**

This scenario is very similar to the one that came before it in terms of the data that was gathered and the way the findings were presented. Figure 4.4, which introduces a new consumer, switches the emphasis of the findings to how the interaction between the two of them impacts the routing mechanism in the network and to what degree it does so. Table 4.8 lists network parameters. Here, Customer 1 starts sending Interest packets at time  $t = 1$  second, while Customer 1 starts sending Interest packets at time  $t = 2$  seconds. Here the volume of data requested doubles as both consumers request data from the provider.

However, the data packet traffic should remain lower than twice the volume. First, when Ant Interest packets and Interest packets arrive separately from Node 3 and Node 5, these are identifiable using the Nonce field of the packet. Only one copy of the data is expected to be sent back into the network. Second, some packets requested by Customer 2, should already be in the content store of intermediate nodes to p1. In particular, almost all these packets should be in the content store for node n2. This is because Customer 2 (Node 1) begins transmitting interest packets a full second after Customer 1 (Node 0) and it will ask for the same sequence of packets that node c1 asked for. The two nodes also send identical Ant Interest packets.

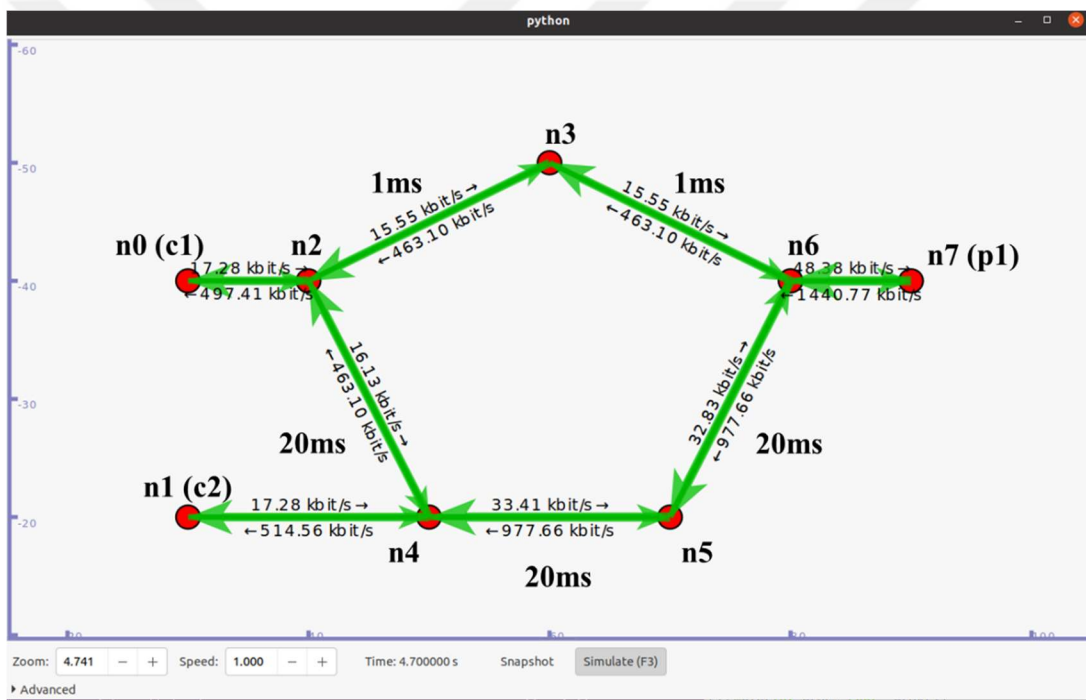


Figure 5.10. Scenario 2. Simulation in ndnSIM visualizer.

In observation of simulations however it was found that this did not work as expected in high traffic. The Content Store lookup process takes some time. If there is too much incoming traffic at the node, the retransmission time is reached before the lookup process can take place. Figures 5.11 to 5.14 show the pheromone concentration on each link. Compared to the pervious simulation it is clear that pheromone levels closer to the results of Scenario 1 than Scenario 3, because, in particular for the second node, much of the data traffic comes from its neighbor nodes that already have this

information. Even in this scenario, the delay in routing data that is available in the Content Store of a neighbor means that sometimes the node needs to its second or third hop neighbor to retrieve data that has already been delivered to its immediate neighbor.

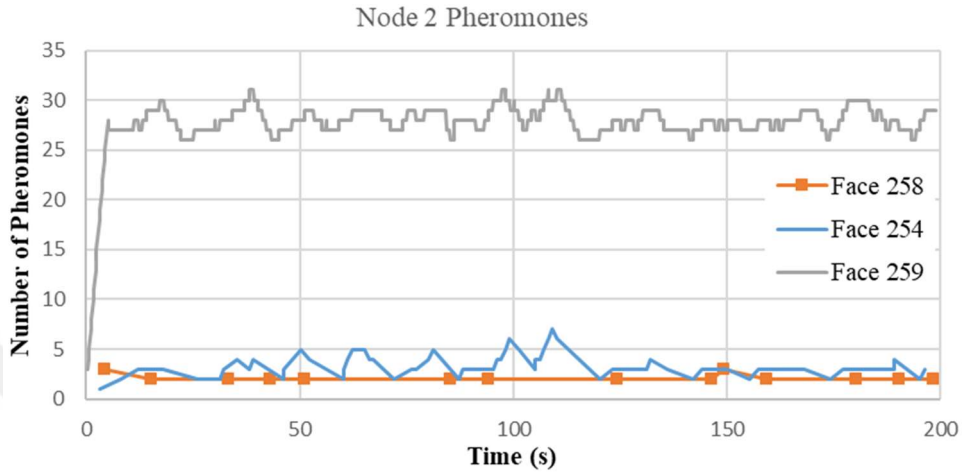


Figure 5.11. Scenario 2, Node 2 pheromone evolution in the faces for CBR traffic.

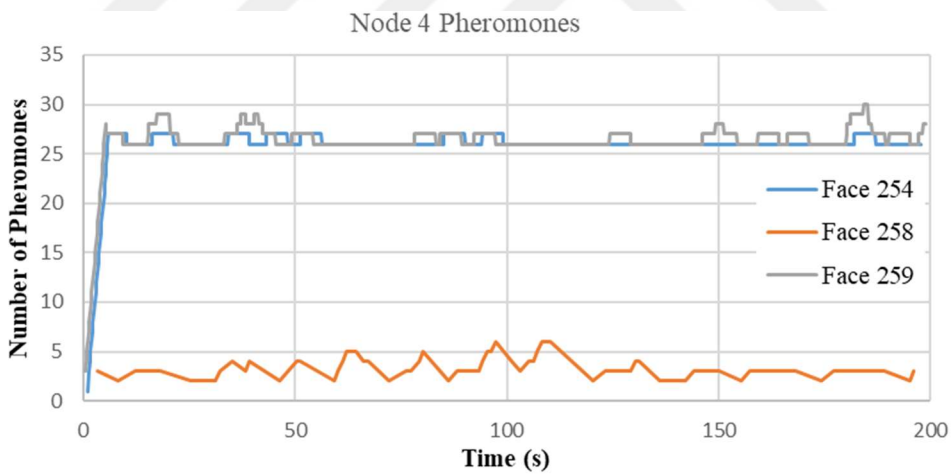


Figure 5.12. Scenario 2, Node 4 pheromone evolution in the faces for CBR traffic.

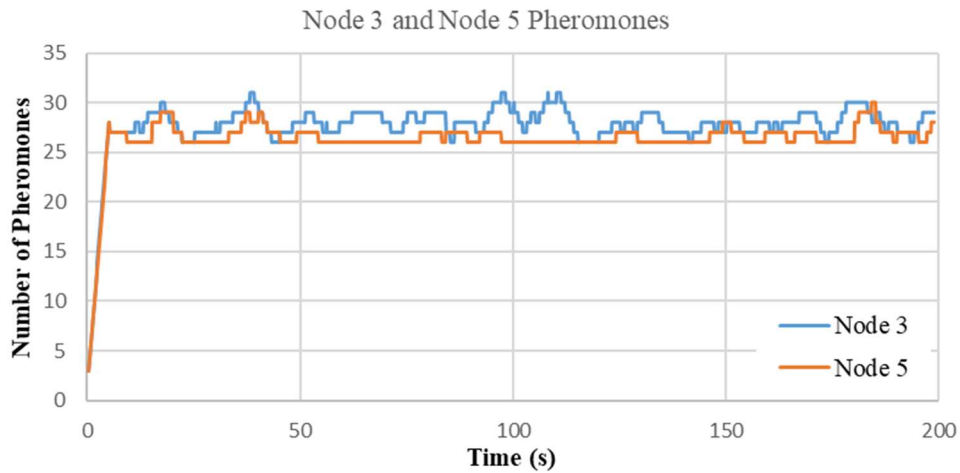


Figure 5.13. Scenario 3, Node 5 pheromone evolution in the faces for CBR traffic.



Figure 5.14. Scenario 2. Packet delay for CBR traffic (a) Customer 1 and (b) Customer 2.

Even with one tenth of the traffic, Figure 5.20 shows that some Interest packets need to be retransmitted in the network because the data they request does not arrive in time. One consequence of this is that Node 2 and Node 4, which are the nodes that connect Customer 1 and Customer 2 to the network, respectively, have three faces.

The third face allows Customer 2 to retrieve Data from Customer 1's Content Store and vice versa. Since Customer 2 retrieves its Data packets from Node 2 and Customer 2, this reduces its delay overall and its probability of requiring retransmission of the Interest packet. This also reduces the pheromone on links in the network, as much of the data from Customer 2 stays local to Node 4 and Node 2. The delay of Customer 1 is reduced but not as significantly. Customer 1 retrieves its data occasionally from Customer 2, but since Customer 1's Interest and Ant Interest packets leave a full second before Customer 2's Interest packet for the same resource, the only time Customer 1 benefits from local storage is when it needs to retransmit its Interest packet.

Node 4 is the first node in the network that customer 2 is connected to. As seen in Table 4.8, Customer 2 will experience a delay of 40ms on the lower path, and a delay of 22ms on the upper path. Customer 2 may be able to collect its data from either Node 4 (its first hop neighbor into the network) directly. Even when this is not possible, it may collect its data from a node one hop away, and those nodes are both at a latency distance of 20ms to Customer 2. Therefore it makes sense that for Customer 2, pheromone levels equal on both the upper and the lower path.

Table 5.1 Content Store messages from Scenario 1.

Node	No-match Data	No-match Ant	Matching Data	Matching Ant
N2	149	994	199	994
N3	117	994	99	994
N4	164	994	0	985
N5	0	994	0	0
N6	117	994	99	993
N7 (Producer)	118	995	99	994

Packet delay shows delays on the order of up to 20 seconds as shown in Figure 5.15. This delay points to packet retransmission or queueing, in the network. It is found that when the size of the Content Store was increased, the delay in the network

increased. This points to the fact that it may be the search for packets in the Content Store which is modeled to take more time. Further simulations will need to be performed to investigate this result. Table 5.1 shows the results.

It was found that Customer 1, which begins data transmission at time 1 second and ends transmission a time 19 seconds had been sent 160 data packets and 1887 Ant packets from the network, while Customer 2, which begins data transmission at time 2 seconds and ends transmission a time 18 seconds had been sent 143 data packets and 1682 Ant packets. For every one of these transmissions, an Interest packet or an Ant Interest packet is sent. Intermediate nodes which receive the Interest or Ant Interest packet from Customer 1 should have received the data transmission and stored this in the Content Store in case another user requested the same data. This second request arrives when Customer 2 begins transmission. The results of the Content Store searches were, however, perplexing. These are summarized in Node 2 matched 40 Interest packets, presumably from Customer 2 even though roughly half or about 70 Interest packets should have been sent to Node 2. It concluded therefore that the Content Store implementation in ndnSIM was not very robust.

### **5.3 Scenario 3**

In this scenario there is a single customer, requesting data from two different producers. The producers are connected to the network through the same node. This scenario eliminates the ability to use the Content Store, the focus is no traffic. Figure 4.5 illustrates the scenario. Table 4.10 lists link parameters. The Customer starts sending Interest packets for Producer 1 at time  $t = 1$  second, ending at time  $t = 19$  seconds. The same Customer starts sending Interest packets aimed at Producer 2 at time  $t = 2$  seconds and ending at  $t = 18$  seconds. The volume of data requested is again doubled as both sets of requests have the same parameters as in Scenario 1. Figure 5.16 shows the simulation running in the ndnSIM visualizer, node labels and link delays have been annotated on this figure for convenience.

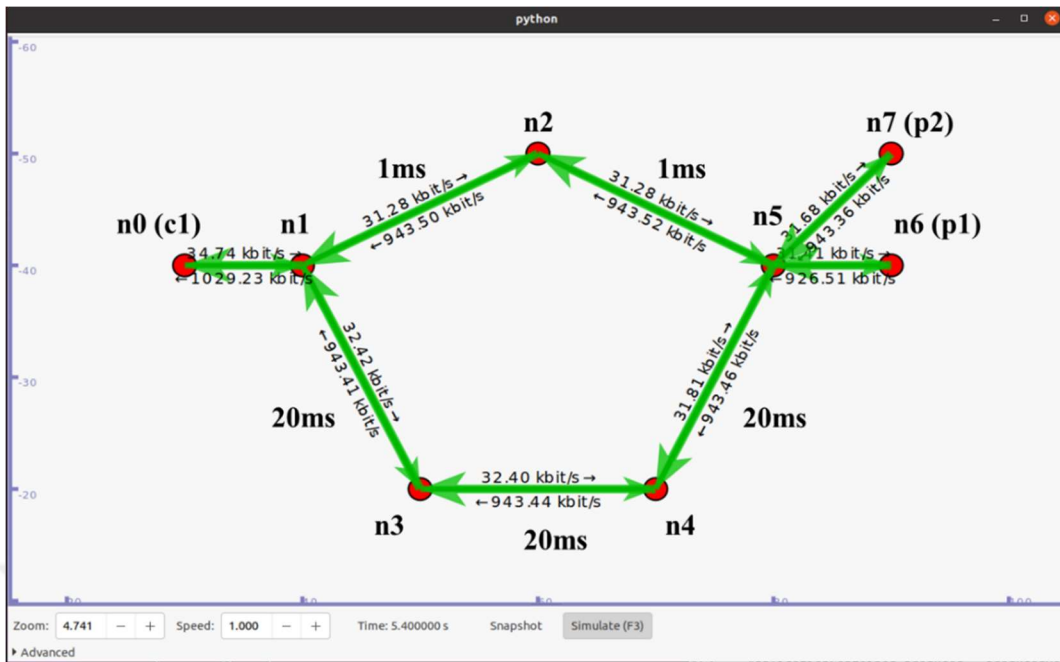


Figure 5.15. Scenario 3. Simulation in ndnSIM visualizer.

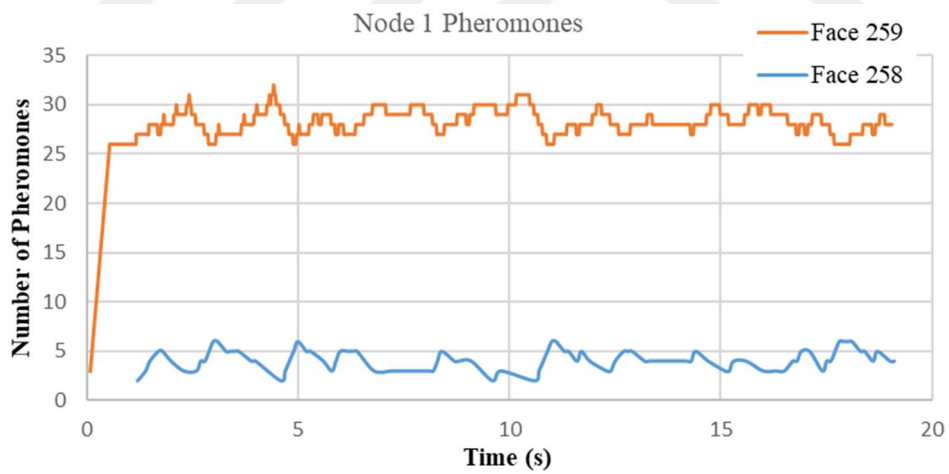


Figure 5.16. Scenario 3, Node 1 pheromone evolution in the faces for CBR traffic.

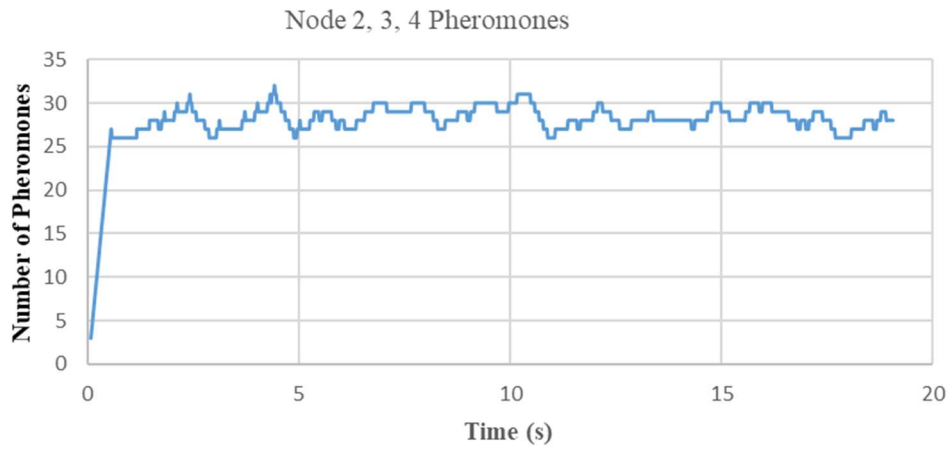


Figure 5.17. Scenario 3, Node 2, 3 and 4 pheromone evolution in the faces for CBR traffic.

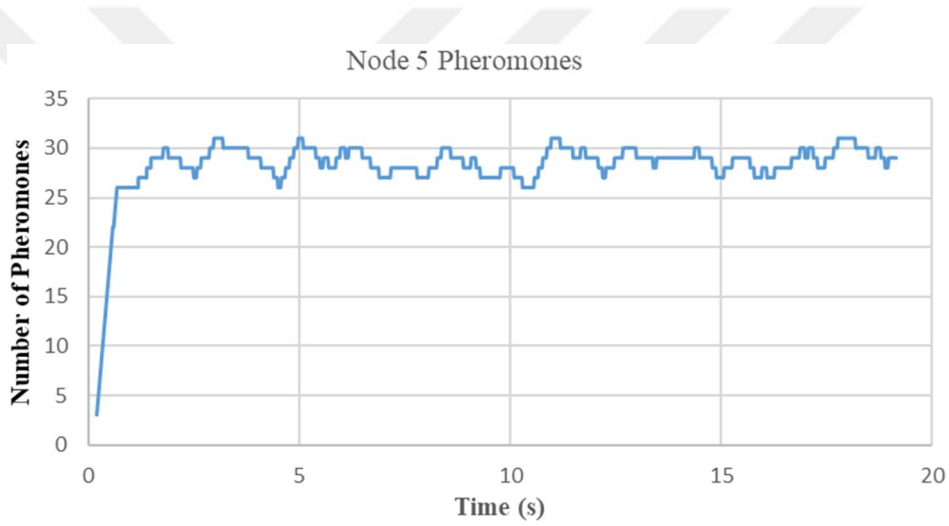
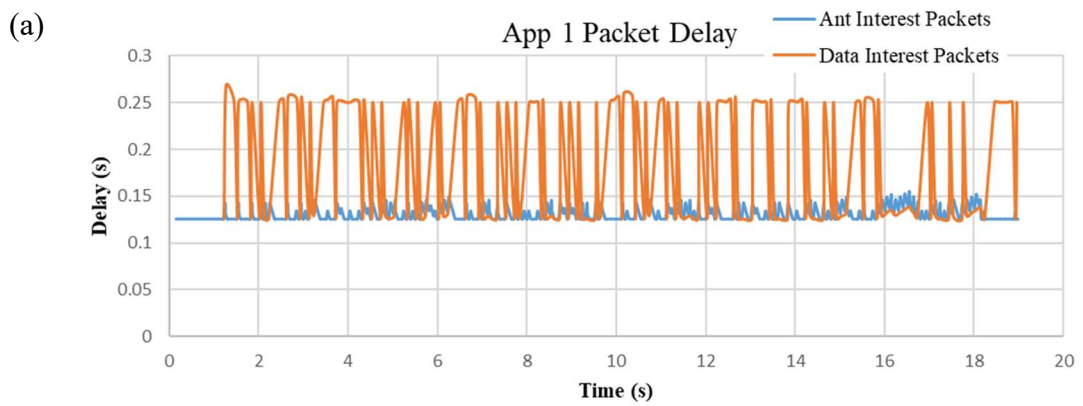


Figure 5.18. Scenario 3, Node 5 pheromone evolution in the faces for CBR traffic.



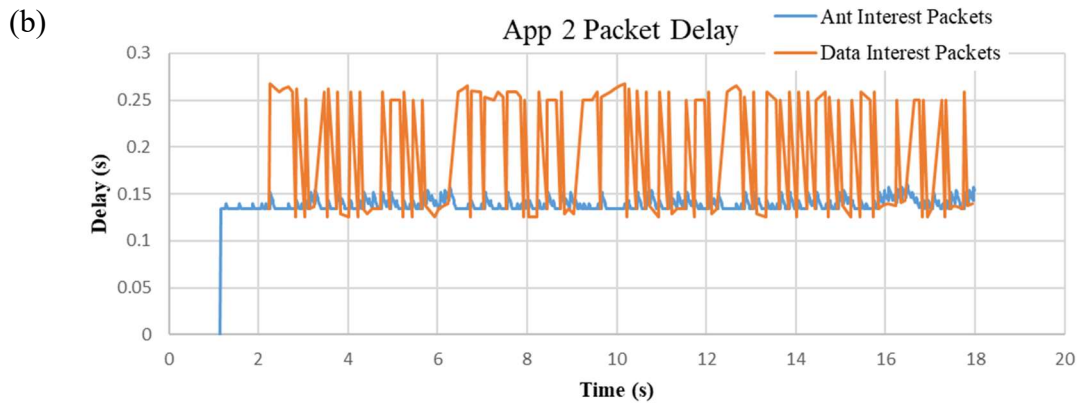


Figure 5.19. Scenario 3. Packet delay for CBR traffic (a) Producer (App) 1 and (b) Producer (App) 2.

The results from this simulation show that since the data cannot be obtained from the Content Store of a closer node, the number of pheromones is much higher especially along the top path. The Ant Interest packets are sent along all paths to the Producers, and they deposit pheromone along the path that the Data is routed back along. While each Interest Ant will trigger a data packet that travels back along the path it first traveled along, at any node along the path that the two paths cross, only the first arriving Data triggered by the same Ant Interest will be allowed to continue. This bottleneck occurs at Node 5 in this example. So the Ant packets will always deposit pheromones along the best path. In this thesis, the Data packets also leave pheromones. However when a Node has a real Interest packet to send, it will only send it along one direction, with preference given to the higher pheromone direction. Thus sometimes Data packets travel along the path with higher delay, leaving a pheromone trail keeping this route active as well. While it may be efficient for Data packets to remove this trail, it also encourages some diversity for routing to reduce the load in the links along the more efficient route.

## **CHAPTER 6. SUMMARY AND CONCLUSIONS**

### **6.1 Introduction**

In the realm of Named Data Networking (NDN), efficient routing mechanisms are paramount for ensuring the smooth flow of data across networks. Traditional routing techniques have served well, but as the volume of data used by different services increases, changes need to be made to the way data is accessed. This study delves into the realm of Swarm Intelligence (SI) to explore its potential as a viable alternative for routing in NDN systems. SI draws inspiration from the collective behavior of decentralized, self-organized systems in nature, such as ant colonies, to solve complex problems. The primary objective of this research is to investigate the feasibility and effectiveness of Swarm Intelligence (SI) as a potential alternative for routing in NDN systems. SI draws inspiration from the collective behaviors observed in natural systems, such as ant colonies and bee swarms, to solve complex problems through decentralized, self-organized methods.

### **6.2 Findings of the study**

The findings of the study provide valuable insights into the efficacy and performance of Swarm Intelligence (SI)-based routing algorithms in Named Data Networking (NDN) environments. Three traffic scenarios were simulated, each focusing on different aspects of routing efficiency and scalability. Through a series of

experiments and analyses, the following key observations and conclusions were drawn:

### **6.2.1 Scenario 1: Validation of SI Implementation**

The study on Ant Colony Optimization (ACO) routing algorithm with window reduction offers significant insights into the behavior and functionality of routing systems within network environments. Through a comprehensive experiment, the research aims to evaluate the core routing concepts and the performance of each module involved in the routing process. By utilizing a swarm of ants as a metaphor for routing agents, the experiment tests the system's ability to discover routes effectively and accurately.

Throughout the experiment, a consumer initiates the routing procedure by dispatching a swarm of ants towards the network, specifying the desired content. Importantly, the experiment maintains consistency by utilizing the same consumer and producer throughout, ensuring stability in the testing environment and facilitating accurate assessment of system performance. The constraints of the experiment are predefined, with the network's topology predetermined to maintain consistency and control.

A key objective of the study is to determine the system's ability to successfully discover routes, populate routing tables with relevant information, and propagate pheromones along established routes. Data collection involves monitoring the Packet Arrival Table (PAT) and Forwarding Information Base (FIB) as the ants navigate the network.

The findings of the study confirm the effectiveness of the ACO routing algorithm with window reduction in achieving its objectives. The system demonstrates successful route discovery. Furthermore, the proper propagation of pheromones by backward agents along specified routes reinforces the efficiency of route discovery and validation of optimal paths.

In conclusion, the study's findings provide valuable insights into the behavior and performance of routing systems within network environments. By successfully

addressing the experiment's objectives and yielding expected results, the study validates the functionality of the ACO routing algorithm.

### **6.2.2 Scenario 2: Pheromone Evolution**

The findings of the experiment shed light on the intricate dynamics of the routing mechanism within the network, particularly emphasizing the use of the Content Store and the interactions between consumers in making routing decisions. The results from this study showed that when the volume of traffic is high, the Content Store lookup can delay packets significantly, and the mechanism may even break down, making the Content Store mechanism useless. Although this is mostly an issue of the simulation platform ndnSIM, it can be seen that similar bottlenecks can occur with too much caching in real systems as well. This issue is important to address in future work.

Overall, the experiment demonstrates the network's ability to effectively manage data objects and utilize caching mechanisms to optimize content delivery. Consumers play a crucial role in data retrieval, with nodes storing data objects throughout the retrieval process and serving them upon receiving matching Interest requests. From the perspective of network goals, the forwarding plane successfully routes data to consumers via the Interest's backward channel, facilitating efficient content delivery. The difference in retrieval times between material acquired directly from the producer and content retrieved from network caches highlights the significance of caching in NDN architecture, with actual results surpassing expectations. This emphasizes the importance of efficient caching strategies in improving overall network performance and content delivery efficiency.

### **6.2.3 Scenario 3: Incorporation of Data Forwarding and Caching**

The findings of Experiment 3 delve into the interplay between data content, node forwarding, and cache capabilities within the network, expanding the focus beyond routing operations to encompass the forwarding process and its implications on overall network activities. In this experiment, a single consumer collects data from two

different producers on the network. This gives insight into how different applications can work together in the network, without the benefit of caching provided by the Content Store.

The results show that the simulation can handle different types of applications well, and while increasing traffic will affect the throughput and delay in the network, it does not cause the delays experienced in Scenario 2.

It is important to acknowledge the limitations of the experiment, particularly regarding its applicability to larger networks. The basic structure and limited number of users in the experimental setup may not fully capture the complexities of larger-scale networks with numerous nodes and connections. Nonetheless, the qualitative approach adopted in the experiment facilitated a detailed inspection of each event, ensuring that routing was executed as planned and intended outcomes were achieved. This meticulous examination provides confidence in the functionality of the routing system, despite potential challenges that may arise in larger network contexts. Overall, the findings underscore the adaptability and effectiveness of the routing system in managing interactions between consumers and optimizing resource allocation within the network.

### **6.3 Implications**

The implications of the study's findings are profound, spanning both theoretical insights and practical applications within the context of Named Data Networking (NDN). Firstly, the successful validation of Swarm Intelligence (SI) as a routing mechanism signifies its potential to significantly enhance routing efficiency in NDN environments. SI-based routing algorithms, with their dynamic adaptability and decentralized decision-making, promise optimized data delivery paths and improved resource utilization. This bears implications for the broader enhancement of network performance and the reduction of latency in NDN systems, critical for meeting the demands of modern networking applications.

Moreover, the scalability and adaptability demonstrated by SI-based routing algorithms are crucial for addressing the evolving landscape of network architectures. With seamless adaptation to changes in network topology and increasing traffic loads,

SI-based routing ensures that routing mechanisms can effectively handle the complexities of large-scale deployments. This scalability not only accommodates the growth of network infrastructures but also fosters resilience and fault tolerance, essential characteristics for robust network operation in dynamic environments.

The decentralized and autonomous nature of SI-based routing algorithms introduces a paradigm shift in routing mechanisms. By enabling routing decisions to be made autonomously based on local information and pheromone trails, SI-based routing enhances network resilience and flexibility. This decentralization not only reduces reliance on centralized control mechanisms but also allows for real-time adaptation to changes in network conditions. As a result, SI-based routing offers greater flexibility and responsiveness compared to traditional routing techniques, paving the way for more adaptive and efficient network operation.

Furthermore, the successful integration of SI into NDN routing opens up avenues for innovation and further research. Future studies could explore optimization techniques, alternative swarm-based algorithms, and hybrid approaches that combine SI with other routing paradigms. These innovations have the potential to further improve routing efficiency, scalability, and adaptability in NDN systems, driving advancements in networking technology. Such advancements hold promise for addressing emerging challenges in network management and enabling the realization of novel applications and services.

Lastly, the practical implications of the study's findings are significant for real-world deployment. Organizations and network operators can leverage SI-based routing algorithms to optimize data delivery, reduce network congestion, and enhance user experience. By incorporating SI into existing NDN infrastructures, organizations can unlock new possibilities for improving network performance and scalability. Ultimately, the successful integration of SI-based routing into NDN environments has the potential to reshape the future of networking technology, driving innovation and advancement in the field.

## **6.4 Limitations of the study**

Despite the promising findings, this study has several limitations:

- The experiments were conducted in controlled environments, which may not fully capture the complexities of real-world network scenarios.
- The scalability of SI-based routing, particularly caching, was only partially addressed, with a focus on specific components affected by network size. Further research is needed to assess its scalability comprehensively.
- The study primarily focused on routing efficiency and did not explore other aspects of network performance, such as latency and throughput.



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