DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

UNIVERSITY OF SAAD DAHLAB BLIDA - 1
Faculty of Sciences
Department of Computer Science
LRDSI

DOCTORAL DISSERTATION (LMD)
Specialization: Networks & Distributed Systems

Efficient Communication in Named Data Networks for Internet of Things

OULD KHAOUA Adel Salah

Examination Committee:
Chair: Prof. N. BOUSTIA, University of Blida 1
Examiner: Prof. M. GUERROUMI, USTHB
Examiner: Prof. S. MERNIZ, University of Constantine 2
Examiner: Dr. A. LOUAZANI, University of Blida 1
Supervisor: Prof. A. BOUKRA, USTHB
Co-supervisor: Dr. F. BEY, University of Blida 1

Blida, 2024

Dedications

I dedicate this work to my beloved parents, Ould Khaoua Mohamed and Ouanoughi Fadhila. Your love, sacrifices, tenderness, unwavering support, and prayers have been the foundation of my education and success. May Allah reward you abundantly and grant you good health.

To my brother, Mohamed Amine, whose constant encouragement and motivation have been instrumental in completing this doctoral study.

Acknowledgments

I am profoundly grateful to my supervisors for their unwavering support and guidance throughout my doctoral journey. I am fortunate to have had the opportunity to work under their supervision. Firstly, I extend my sincere appreciation to my main supervisor, Prof. A. Boukra, from the University of Houari Boumediene for Science & Technology (USTHB), Algeria, whose invaluable advice, availability, and trust in my abilities have been instrumental in shaping my research. Prof. Boukra's extensive research experience and expertise have enriched my understanding of the research methodology and fostered in me the resilience necessary for the effective formulation, articulation, and defense of research ideas.

I also extend my heartfelt thanks to my co-supervisor, Dr. F. Bey, from the University of Blida 1, Algeria, for her invaluable guidance and support throughout my doctoral research. Dr. Bey's feedback and encouragement have been indispensable to my academic growth, and I am deeply grateful for her contributions during this research.

I sincerely thank Prof. N. Boustia, from University of Blida 1, for accepting to be the Chair of my Examination Committee. My heartfelt gratitude goes to Prof. M. Guerroumi, from USTHB, Prof. S. Merniz, from University of Constantine 1, and Dr. A. Louazani, from University of Blida 1, for agreeing to be part of the examination committee. I am deeply appreciative of the time and effort they dedicated to examining this thesis, which is a testament to their commitment to academic excellence.

I would also like to express my heartfelt thanks to all the members of LRDSI and the Department of Computer Science at the University of Blida 1. Your great support, whether through insightful discussions, constructive feedback, or moral encouragement, has been instrumental in shaping this work. I am truly thankful for your involvement, which has made this journey more rewarding.

Abstract

Integrating low-cost sensing and actuating devices into the Internet has propelled the evolution of the Internet of Things (IoT), characterized by many small smart devices, or "things," equipped with sensing, communication, and computing capabilities. However, limited processing power, memory, and energy resources often constrain these devices. Additionally, they frequently operate within Low-power and Lossy Networks (LLNs), leveraging IEEE 802.15.4 communication technologies to facilitate data exchange within the IoT ecosystem.

Communication in LLNs poses significant challenges, particularly ensuring reliability and adapting to dynamic network topologies resulting from lossy links and device mobility inherent in IoT applications. Named Data Networking (NDN) has emerged as a promising alternative to IP for addressing the communication needs of IoT applications. NDN's data-centric model aligns well with IoT requirements, facilitating user mobility and data sharing through features like caching, naming, and stateful forwarding. However, when deployed over LLNs, nodes in NDN rely on the broadcast nature of the shared wireless medium to forward interest packets to their neighboring nodes, which often results in the broadcast storm problem.

This study is among the first to explore the effectiveness of probabilistic techniques for interest forwarding in NDN over LLNs to mitigate the adverse effects of the broadcast storm problem while adhering to LLN constraints. To this end, three distinct probabilistic forwarding strategies—Probabilistic Forwarding (PF), GOSSIP, and Distance-based Probabilistic Interest Forwarding (DPIF)—are introduced. While PF employs probabilities for forwarding control, GOSSIP augments PF through flooding and duplicate control. On the other hand, DPIF augments GOSSIP through propagation control. The rationale for proposing these strategies is to assess the efficacy of combining probabilities with different control mechanisms for interest forwarding in NDN over LLNs, thereby providing a comprehensive understanding of their capabilities and limitations under different operating conditions.

Extensive simulations are conducted to undertake the first comprehensive evaluation of interest forwarding strategies in NDN over LLNs. This evaluation encompasses a performance analysis of PF, GOSSIP, and DPIF alongside well-established existing strategies, including Blind Flooding (BF), Deferred Blind Flooding (DBF), Learning-based Adaptive Forwarding Strategy (LAFS), and Provider Aware Forwarding (PAF), across a range of scenarios. Extensive simulation results are collected to quantify and analyze the performance advantages of probabilistic strategies for interest forwarding in NDN over LLNs in terms of packet retransmissions, retrieval latency, success rates, and energy consumption.

Keywords: IEEE 802.15.4, Interest forwarding, IoT, LLN, NDN, NDNsim, Simulation.

Résumé

L'intégration de dispositifs de détection et d'actionnement à faible coût dans l'Internet a propulsé l'évolution de l'Internet des objets (IoT), caractérisé par une myriade de petits dispositifs intelligents, ou "objets", équipés de capacités de détection, de communication et de calcul. Cependant, ces dispositifs sont souvent limités par des ressources de traitement, de mémoire et d'énergie restreintes. De plus, ils fonctionnent fréquemment dans des réseaux à faible consommation d'énergie et à perte (LLNs), utilisant les technologies de communication IEEE 802.15.4 pour faciliter l'échange de données au sein de l'écosystème IoT.

La communication dans les LLNs pose des défis significatifs, notamment en ce qui concerne la fiabilité et l'adaptation aux topologies de réseau dynamiques résultant des liens instables et de la mobilité des dispositifs inhérents aux applications IoT. Le Named Data Networking (NDN) a émergé comme une alternative prometteuse à l'IP pour répondre aux besoins de communication des applications IoT. Le modèle centré sur les données du NDN s'aligne bien avec les exigences de l'IoT, facilitant la mobilité des utilisateurs et le partage de données grâce à des fonctionnalités telles que l'utilisation du cache, le nommage des données et le transfert avec état. Cependant, lorsqu'e NDN est déployé sur des LLNs, les nœuds du NDN s'appuient sur la nature de diffusion du médium sans fil partagé pour transmettre des paquets d'intérêt à leurs nœuds voisins, ce qui entraîne souvent le problème de la tempête de diffusion.

Cette étude est parmi les premières à explorer l'efficacité des techniques probabilistes pour le transfert des intérêts dans le NDN sur des LLNs afin d'atténuer les effets néfastes du problème de la tempête de diffusion tout en respectant les contraintes des LLNs. À cette fin, trois stratégies de transfert probabilistes distinctes—le transfert probabiliste (PF), GOSSIP et le transfert probabiliste basé sur la distance (DPIF)—sont introduites. Alors que PF utilise des probabilités pour contrôler le transfert, GOSSIP améliore PF par le biais du flooding et du contrôle des paquets en double. D'autre part, DPIF améliore GOSSIP par le contrôle de la propagation. La justification de ces stratégies est d'évaluer l'efficacité de la combinaison des probabilités avec différents types de mécanismes de contrôle pour le transfert des intérêts dans le NDN sur des LLNs, fournissant ainsi une compréhension complète de leurs capacités et limitations dans différentes conditions d'exploitation.

Des simulations sont menées pour entreprendre la première évaluation complète des stratégies de transfert des intérêts dans le NDN sur des LLNs. Cette évaluation comprend une analyse des performances de PF, GOSSIP et DPIF, ainsi que des stratégies existantes bien établies telles que BF, DBF, LAFS et PAF, dans une gamme de scénarios. Des résultats de simulation approfondis sont recueillis pour quantifier et analyser les avantages de performance des stratégies probabilistes pour le transfert des intérêts dans le NDN sur des LLNs en termes de retransmissions de paquets, de latence de récupération, de taux de succès et de consommation d'énergie.

Mots-clés: IEEE 802.15.4, transfert des intérêts, IoT, LLN, NDN, NDNsim, Simulation.

الملخص

أدى دمج أجهزة الاستشعار والأجهزة التنفيذية منخفضة التكلفة في الإنترنت إلى تطور إنترنت الأشياء(IoT) ، الذي يتميز بالعديد من الأجهزة الذكية الصغيرة، أو "الأشياء"، المجهزة بقدرات الاستشعار والاتصال والحوسبة. ومع ذلك، غالباً ما تكون هذه الأجهزة محدودة بقدرات معالجة وذاكرة وموارد طاقة محدودة. بالإضافة إلى ذلك، تعمل هذه الأجهزة بشكل متكرر ضمن شبكات الطاقة المنخفضة والخسارة (LLNs) ، مستفيدة من تقنيات الاتصال IEEE 802.15.4 لتسهيل تبادل البيانات داخل نظام إنترنت الأشياء.

تشكل الاتصالات في شبكات LLNs تحديات كبيرة، لا سيما في ضمان الموثوقية والتكيف مع الطوبولوجيا الديناميكية للشبكة الناتجة عن الروابط الخسارة وتنقل الأجهزة المتأصلة في تطبيقات إنترنت الأشياء. ظهر التوجيه المعتمد على البيانات المسماة (NDN) كبديل واعد لبروتوكول الإنترنت (IP) لمعالجة احتياجات الاتصالات في تطبيقات إنترنت الأشياء. يتماشى نموذج NDN القائم على البيانات بشكل جيد مع متطلبات إنترنت الأشياء، حيث يسهل تنقل المستخدمين ومشاركة البيانات من خلال ميزات مثل التخزين المؤقت والتسمية والتوجيه بالحالة. ومع ذلك، عند نشره على LLNs ، تعتمد العقد في NDN على الطبيعة البثية للوسط اللاسلكي المشترك لتمرير حزم الاهتمام إلى العقد المجاورة، مما يؤدي غالبًا إلى مشكلة عاصفة البث.

تعد هذه الدراسة من بين الأوائل التي تستكشف فعالية التقنيات الاحتمالية لتوجيه الاهتمام في NDN عبر LLNs لتخفيف الآثار السلبية لمشكلة عاصفة البث مع الالتزام بقيود LLN. لهذا الغرض، تم تقديم ثلاث استراتيجيات توجيه احتمالية متميزة—التوجيه الاحتمالي (PF)، وGOSSIP، والتوجيه الاحتمالي المعتمد على المسافة (DPIF). في حين يستخدم PF الاحتمالات للتحكم في التوجيه، يعزز GOSSIP الاستراتيجية PF من خلال الفيضانات والتحكم في التكرار. من ناحية أخرى، DPIF يعززالاستراتيجية GOSSIP من خلال التحكم في الانتشار. الهدف من اقتراح هذه الاستراتيجيات هو تقييم فعالية الجمع بين الاحتمالات مع أنواع مختلفة من آليات التحكم لتوجيه الاهتمام في NDN عبرLLNs ، وبالتالي توفير فهم شامل لقدراتها وحدودها في ظل ظروف التشغيل المختلفة.

تم إجراء محاكاة مكثفة لتنفيذ أول تقييم شامل لاستراتيجيات توجيه الاهتمام في NDN عبر LLNs. يتضمن هذا التقييم تحليل أداء PFو GOSSIP وDPIF، إلى جانب الاستراتيجيات الموجودة والمعروفة جيداً بما في ذلك الفيضانات العمياء(BF) ، وتأجيل الفيضانات العمياء (DBF) ، واستراتيجية LAFS و PAF، عبر مجموعة من السيناريوهات. تم جمع نتائج المحاكاة الواسعة لقياس وتحليل مزايا الأداء للاستراتيجيات الاحتمالية لتوجيه الاهتمام في NDN عبر LLNs من حيث إعادة إرسال الحزم، وزمن الاسترجاع، ومعدلات النجاح، واستهلاك الطاقة.

الكلمات المفتاحية : IEEE 802.15.4 ، توجيه الاهتمام، إنترنت الأشياء، LLN، NDN، NDNsim، المحاكاة.

Table of Contents

List of Figures

List of Tables

List of Algorithms

List of Abbreviations/Symbols

Abbreviation/Symbol	**Meaning**
ADU	Application Data Unit
BF	Blind Flooding
CS	Content Store
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D	Distance Table
DBF	Deferred Blind Flooding
DMIF	Dual Mode Interest Forwarding
DPIF	Distance-Based Probabilistic Forwarding
FIB	Forwarding Interest Base
GIF	Geographic Interest Forwarding
GOSSIP	Gossip-based forwarding strategy
ICN	Information Centric Network
IoT	Internet of Things
IP	Internet Protocol
k	Number of flooding hops
LAFS	Learning-based Adaptive Forwarding Strategy
LFBL	Listen First Broadcast Later
LLN	Low power and Lossy Network
m	Duplicate threshold
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MTU	Maximum Transmission Unit
NDN	Named Data Network
p	Probability
PAF	Producer Aware Forwarding
PF	Probabilistic Forwarding
PHY	Physical sub-layer
PIT	Pending Interest Table
RLF	Reinforcement Learning Forwarding
TCP	Transmission Control Protocol
VANET	Vehicular Ad hoc Network
WSN	Wireless Sensor Network
X	Intermediate node
Y	Neighboring node of X
Δ	Listening period (in seconds)
ρ	Time interval (in seconds) for updating the distance to the producer

1. General Introduction

1.1 Context of the research

The Internet of Things (IoT) [1-3] has transformed human interactions with the environment by connecting everyday objects to the Internet, enabling autonomous data collection and exchange. IoT encompasses a vast network of interconnected devices, ranging from sensors and actuators to smartphones and wearables, facilitating automation, monitoring, and data-driven decision-making across diverse domains. Low-power and Lossy Networks (LLNs) [4] are pivotal within the IoT ecosystem, particularly in resource-constrained or challenging environments. LLNs support communication among devices with limited processing power, memory, and energy resources, often relying on low-cost, low-bandwidth wireless technologies like IEEE 802.15.4. These networks are prevalent in many applications, including smart homes, industrial automation, environmental monitoring, and smart cities, necessitating reliable communication despite intermittent connectivity, high packet loss, and limited bandwidth [5, 6].

Today, state-of-the-art wireless networks, including LLNs, still rely on the TCP/IP protocol stack initially designed for the static wired Internet [7]. This protocol stack includes traditional IP-based routing at the network layer and point-to-point transmissions at the link layer. However, the design of TCP/IP was primarily inspired by the old public telephone network under the assumption that most communications would involve establishing a connection between two static end-hosts through which text data is exchanged. It is becoming increasingly clear that existing TCP/IP networks are inadequate in addressing the requirements of IoT applications [8-10]. Such requirements include managing complex and dynamic network topologies resulting from frequent mobility, efficiently linking content with its location for efficient retrieval, implementing effective power management, and ensuring secure data exchange.

In response to the limitations inherent in conventional IP networks, Information-Centric Networking (ICN) [11, 12] has emerged as a new networking paradigm. ICN retrieves data based on "names" rather than host IP addresses, representing a significant departure from the established norms. ICN is projected to simplify application development by eliminating the requirement for address resolution and host localization, which makes it well-suited to the communication requirements of IoT and can easily accommodate user mobility [13]. Moreover, ICN security, which is based on data, is also more adaptable than IP to meet the security needs of IoT systems [13, 14].

Named Data Networking (NDN) [15, 16, 17] stands out as one of the most prominent implementations of ICN, offering a robust foundation for various network environments, including IoT [18, 19, 20]. NDN's acceptance stems from its advantageous features, notably its distinctive naming scheme, stateful forwarding mechanism, and efficient caching strategies. At the core of NDN's architecture lies its ability to uniquely identify content through a URL-like naming structure. This naming convention facilitates seamless data retrieval, where consumers issue interest packets to request specific content, prompting data producers to deliver corresponding data packets. One of the significant advantages of NDN is its departure from traditional IP-centric models, as it fosters IP address-free communication. This design choice simplifies data retrieval and enhances security and privacy by abstracting communication to content-centric operations. Furthermore, NDN's stateful forwarding and caching mechanisms enable efficient data delivery by leveraging network-level caching and reducing unnecessary data transmissions. Additionally, NDN's inherent support for extensive mobility ensures seamless data access even in dynamic network environments, eliminating the need to establish and maintain end-to-end connections between hosts. This combination of features positions NDN as a compelling solution for IoT deployments, offering scalable, secure, and efficient data dissemination in diverse network scenarios.

Among other attractive features of NDN lies in its ability to store data within the network through caching at intermediate devices. This approach enables NDN to proactively push content closer to users instead of solely relying on data storage in servers. This benefit results from NDN leveraging technological advancements, increasing device memory capacities. Furthermore, the caching mechanism, coupled with the absence of the need to establish connections with servers, facilitates multiple end hosts requesting the same piece of content, thereby inherently supporting multicast communication [15. 16].

Integrating NDN into the current networking landscape requires fundamentally modifying existing IP-based equipment, protocols, and applications [21]. This is because the NDN paradigm operates on content names rather than traditional host addresses. Additionally, convincing enthusiasts of IP and industrial players about the benefits of NDN poses a considerable challenge, particularly when IP solutions suffice for existing applications. Fortunately, in recent years, numerous studies have explored the suitability of NDN for IoT, enhancing its viability and relevance. This increased focus on NDN's potential in IoT applications has strengthened its position as a promising networking paradigm. Consequently, integrating NDN into LLNs offers a feasible approach to incorporating NDN into IoT systems, considering the prevalence of constrained devices, such as LLNs, in IoT environments. Moreover, even with IP, the low-end IoT sector is still in the developmental stage. This presents a unique opportunity to integrate NDN into IoT solutions relatively quickly. By capitalizing on this opportunity, NDN can emerge as a significant and impactful component of IoT ecosystems, offering numerous benefits and driving innovation in the field.

The original studies on NDN [15, 16] have proposed Blind Flooding (BF) as a strategy for forwarding interest packets to search for data producers. In BF, each intermediate node forwards interest packets until a corresponding data producer is located. This method presents several notable advantages, including its simplicity, straightforward implementation, and resilience, particularly in scenarios characterized by mobility and sporadic connectivity. This resilience stems from the widespread dissemination of interest packets throughout the network, ensuring a comprehensive exploration of the network to locate relevant data producers efficiently. However, the challenges become apparent when NDN is deployed over wireless networks, where nodes typically operate with a single communication interface conforming to established standards such as IEEE 802.15.4 [4] or IEEE 802.11 [22]. The broadcast nature of the shared wireless medium often leads to a range of issues, collectively known as the broadcast storm problem [23]. These issues include redundant packet retransmissions, excessive channel contention, and frequent packet collisions, which can severely impact network performance and efficiency.

1.2 Research motivations

Numerous interest forwarding strategies [24-34] have been developed to mitigate the degrading effects arising from the broadcast storm problem in NDN deployments over wireless networks. Additionally, various lightweight strategies have been specifically devised for interest forwarding in NDN over LLNs [29, 27, 30-33]. Prominent examples include Neighborhood-Aware Interest Forwarding (NAIF) [27], Deferred Blind Flooding (DBF) [30], Learning-based Adaptive Forwarding Strategy (LAFS) [31], Dual-Mode Interest Forwarding (DMIF) [32], and Reinforced Learning Forwarding (RLF) [33].

Our extensive review of the research literature has revealed that most existing strategies [24-34] integrate one or more control mechanisms to alleviate the broadcast storm problem and achieve efficient data retrieval. These mechanisms include *forwarding, flooding*, *duplicate*, and *propagation control*. Forwarding control determines which network nodes are authorized to retransmit interest packets. Flooding control regulates the spatial extent to which interest packets can disseminate across all directions within the network, preventing excessive redundant interest retransmissions, which may increase the risk of network congestion. Duplicate control identifies and discards duplicate interest packets arriving at an intermediate node, thereby conserving network resources by avoiding redundant interest retransmissions. Additionally, propagation control is implemented to ensure that interests advance only within specific network regions hosting potential data producers, enabling targeted data retrieval and optimizing network performance.

In DBF [30], an intermediate relay node implements a duplicate control mechanism by employing a random listening period upon receiving an interest packet. This listening period allows the node to discard any received duplicate interest packets. Subsequently, once the listening period concludes, the node transitions to forwarding control, where it assesses the number of received duplicates before deciding on interest retransmission. Notably, retransmission is canceled if the duplicates exceed a predetermined threshold, thereby reducing traffic inside the network, and thus reducing packet collisions. The Listen First Broadcast Later (LFBL) [34] strategy builds upon DBF by introducing propagation control as a primary step. In LFBL, nodes determine their eligibility for interest forwarding based on their proximity to data producers, prioritizing nodes closer to the source for efficient data delivery. Upon qualifying for interest forwarding, a node activates duplicate control as in DBF, monitoring duplicate interest packets for a duration tailored to its distance from the producer.

Examining the current literature on forwarding strategies has revealed that probabilistic schemes have undergone extensive investigation within various wireless networks with traditional TCP/IP settings, including Mobile Ad hoc Networks (MANETs) [35-38], Wireless Sensor Networks (WSNs) [39-42], and Vehicular Ad hoc Networks (VANETs) [43-46]. Their appeal lies in their simplicity and ease of implementation, making them a compelling alternative to existing forwarding strategies as they can leverage probabilities to implement efficient forwarding control mechanisms. Owing to their inherent ability to adjust the forwarding probability to effectively reduce redundant interest retransmissions, they can effectively address challenges posed by the broadcast storm problem. Furthermore, the probabilistic schemes align well with the constrained capabilities of LLNs concerning computation, communication, and energy usage. Nevertheless, our extensive review of the research literature has highlighted a significant gap in evaluating the merits of these schemes within the specific context of NDN over LLNs.

Furthermore, probabilistic schemes can struggle to maintain good network reachability when the forwarding probability is set low, leading to packets failing to reach their intended destinations. To remedy this, gossip-based techniques [47-49], although inherently probabilistic, have demonstrated the ability to ensure high reachability levels even with low forwarding probabilities [50]. This has motivated the authors in a recent study [51] to introduce the GOSSIP strategy for interest forwarding in NDN over MANETs utilizing IEEE 802.11 links. Despite their promising attributes, research exploring the suitability of gossip-based techniques for interest forwarding in NDN over LLNs remains limited.

In addition to the observations mentioned above, examining the current research literature has unveiled that while most existing forwarding strategies employ duplicate control to reduce retransmissions, they often suffer from indiscriminately propagating interests across the network, resulting in excessive retransmissions due to a lack of propagation control. Conversely, the few strategies that employ propagation control to regulate interest dissemination based on network regions cannot often effectively handle challenges posed by consumer or producer mobility, leading to suboptimal forwarding decisions and potential delays in data retrieval. Thus, there is an urgent need to develop and evaluate novel forwarding strategies that can strike a balance between efficient duplicate control and targeted interest propagation, considering the dynamic nature of LLNs and the evolving communication requirements of NDN-based IoT applications.

Having said the above, our review of the current research literature has also uncovered that the evaluation of existing forwarding strategies has predominantly involved comparative analyses against DBF and BF. Additionally, most existing performance studies [30-33] have typically focused on static or mobile scenarios, lacking comprehensive evaluations encompassing both conditions. This introduces a knowledge gap regarding the relative performance merits of these strategies in stationary versus mobile settings. Addressing this gap is crucial to gaining a holistic understanding of the effectiveness of forwarding strategy across varying network conditions and mobility scenarios, thereby providing valuable insights for optimizing data retrieval in NDN over LLN deployments. Closing this gap would contribute significantly to enhancing the efficiency of forwarding strategies in real-world scenarios, ensuring high data delivery and network performance.

1.3 Research contributions

Motivated by the above observations, our present research work makes several original contributions to the field of interest forwarding strategies in NDN over LLNs. These contributions are summarized below in the order in which they are reported in this dissertation.

A new classification of interest forwarding strategies for NDN over LLNs: This research introduces a novel classification framework for interest forwarding strategies specifically designed for NDN over wireless networks, including LLNs. Our classification system categorizes these strategies based on the specific control mechanisms they employ, providing a comprehensive taxonomy for analyzing and understanding their operational principles.

A key highlight of this work is its emphasis on lightweight strategies tailored for resource-constrained LLN devices. By focusing on these lightweight strategies, we aim to address the unique challenges posed by LLN environments, such as limited computational capabilities and energy constraints. Our thorough analysis of these strategies includes an examination of their advantages, limitations, and suitability for various LLN deployment scenarios. Moreover, through our classification framework, we offer valuable insights regarding the design of interest forwarding strategies for NDN over LLNs. This contribution not only enhances the understanding of existing strategies but also paves the way for developing novel and efficient forwarding techniques tailored to the specific requirements of LLN deployments.

The first exploration of probabilistic forwarding strategies in NDN over LLNs: Our research is among the first to explore the effectiveness of probabilistic and gossip-based techniques for interest forwarding within the framework of NDN over LLNs. We introduce two forwarding strategies, namely Probabilistic Forwarding (PF) and GOSSIP, designed explicitly for efficient data retrieval and dissemination in LLN environments. The PF strategy leverages a probabilistic mechanism to implement forwarding control. On the other hand, the GOSSIP strategy incorporates flooding, forwarding, and duplicate control to reduce unnecessary interest retransmissions to effectively mitigate the deleterious impact of the broadcast storm problem.

Subsequently, our study delves into a comprehensive performance evaluation of these probabilistic techniques to identify the optimal settings for key parameters governing the operations of their adopted control mechanisms. By systematically analyzing crucial performance metrics such as data retrieval latency and energy efficiency under varying parameter configurations, we aim to determine the most effective and efficient settings for these probabilistic forwarding strategies when NDN are deployed over LLNs.

Introduction of a novel approach to interest forwarding in LLNs: Building on the exploration of probabilistic techniques, this work delves into the effectiveness of integrating propagation control with probabilistic forwarding in NDN over LLNs. This investigation culminates in the development of a novel forwarding strategy, referred to as Distance-based Interest Forwarding (DPIF). DPIF synergistically combines various control mechanisms to address the limitations of existing solutions.

The key innovation of DPIF lies in its ability to leverage estimated distances to data producers alongside probabilities to optimize the forwarding process, thereby enhancing network efficiency and reducing unnecessary retransmissions. Notably, DPIF achieves these improvements with minimal modifications to NDN structures and packets, ensuring compatibility with the fundamental principles of the NDN paradigm.

The first comprehensive performance evaluation of forwarding strategies in NDN over LLNs: While existing research has surveyed various forwarding strategies designed for NDN over wireless networks, including LLNs, these surveys have predominantly focused on comparing the "conceptual" aspects of these techniques. However, a significant research gap exists concerning the lack of comprehensive performance evaluations of these strategies. This study bridges this gap by presenting the first exhaustive performance evaluation of major forwarding strategies proposed for NDN over LLNs to elucidate their performance characteristics across diverse network environments.

Our evaluation study encompasses an in-depth analysis of seven forwarding strategies, listed alphabetically as BF, DBF [30], LAFS [31], and PAF [28]. Through extensive experimentation across diverse network configurations and traffic conditions, we seek to gain novel insights into the performance behavior of these strategies in various dynamic operating conditions. Another highlight of our study is the analysis of the performance merits of PAF [28], specifically when deployed over IEEE 802.15.4 communication technology. This focused analysis provides a deeper understanding of PAF's performance behavior in NDN over LLNs.

1.4 Organization of the dissertation

The rest of this dissertation is organized as follows:

Chapter 2: Internet of Things and Low-Power and Lossy Networks

This chapter delves into the foundational aspects of the IoT and LLNs, providing a comprehensive understanding of their applications, system architectures, and the underlying technologies that enable their functionality.

Chapter 3: Named Data Networking

Here, we explore the NDN paradigm in detail, elucidating the data structures utilized by intermediate relay nodes for processing interest and data packets. Furthermore, this chapter outlines the unique challenges and considerations that arise when implementing NDN over LLNs, mainly due to the distinctive characteristics of the wireless communication medium.

Chapter 4: A Review of Interest Forwarding Strategies in NDN over LLNs

This chapter conducts a systematic review of existing interest forwarding strategies within the context of NDN over wireless networks, specifically focusing on their adopted control mechanisms to alleviate the degrading impact of the broadcast storm problem and their adaptability to LLN environments.

Chapter 5: Probabilistic Interest Forwarding for NDN over LLNs

In this chapter, we introduce and analyze two strategies, Probabilistic Forwarding (PF) and GOSSIP, designed for interest forwarding in NDN over LLNs. An extensive performance analysis is conducted to elucidate the impact of critical parameters used in the forwarding process in these strategies.

Chapter 6: Distance-based Interest Forwarding (DPIF) for NDN over LLNs

Here, we present a new strategy, Distance-based Interest Forwarding (DPIF), tailored for interest forwarding in NDN over LLNs. An in-depth performance analysis is conducted to identify the optimal setting of critical parameters used in the forwarding process, aiming to enhance efficiency and performance.

Chapter 7: Comprehensive Performance Evaluation of Forwarding Strategies in NDN over LLNs

This chapter undertakes a comprehensive performance evaluation, comparing PF, GOSSIP, DPIF, and established strategies such as BF, DBF, LAFS, and PAF across various scenarios. Through extensive analysis, we provide insights into their comparative strengths, weaknesses, and suitability for deployment in different LLN environments.

Chapter 8: Conclusions and Future Directions

Finally, Chapter 8 consolidates the findings from the preceding chapters, summarizes the main contributions of this research, and outlines future directions for enhancing interest forwarding strategies in NDN over LLNs, thus contributing to the continued development of NDN over LLNs for the IoT era.

2. Internet of Things and Low-Power and Lossy Networks

2.1 Introduction

The Internet of Things (IoT) represents a transformative leap in technology, ushering in a new era where interconnected devices seamlessly communicate and autonomously collaborate to enhance efficiency, productivity, and convenience across various domains, significantly impacting every aspect of human life [1-3]. The primary objective of this chapter is to elucidate the fundamental concepts, applications, and challenges posed by IoT. The chapter then introduces Low-power and Lossy Networks (LLNs), a communication technology specifically designed to facilitate seamless connectivity and data exchange within the IoT ecosystem. Furthermore, the chapter explores IEEE 802.15.4 communication technology [4], one of the most prevalent implementations of LLNs. By providing a comprehensive overview of IoT and LLNs, this chapter lays the groundwork for understanding the subsequent chapters, particularly regarding the main contributions made by this research work.

The remainder of the chapter is organized as follows. Section 2.2 offers a background on IoT, exploring its applications and addressing the challenges posed by these applications. Section 2.3 delves into various technologies for LLNs, providing insights into their functionalities. Subsequently, the focus shifts to IEEE 802.15.4 communication technology in Section 2.4, examining its implementation within LLNs. Finally, Section 2.5 summarizes the key concepts discussed in this chapter.

2.2 Internet of Things

Significant strides in technological innovation, particularly in the realm of electronic miniaturization, have heralded a transformative era marked by the proliferation of billions of interconnected devices. This paradigm shift, characterized by the convergence of physical and digital realms, is exemplified by the emergence of IoT. Enabled by the widespread availability of affordable systems on modules and cheap wireless communication technologies, this phenomenon transcends traditional boundaries, facilitating seamless connectivity between people, objects, and systems across the global digital landscape.

The IoT can be viewed as the most recent advancement of the Internet, assuming a critical function in delivering access to services and information worldwide. As early as 2008, the number of interconnected objects surpassed the global human population, marking a significant shift in the digital landscape [52]. This trend continued, with IoT connections experiencing a significant surge of 45% by 2016, reaching 410 million, reflecting the widespread adoption and integration of IoT devices across various sectors [53]. The automotive industry exemplifies this growth, with the percentage of connected vehicles expected to climb from 10% in 2012 to a staggering 90% by 2020 [53]. Looking ahead, projections indicate that the global tally of connected devices will reach an unprecedented 29 billion by

2030, far exceeding the estimated 4 billion connected individuals [54].

Typically, an IoT system comprises a multitude of wireless devices deployed within various infrastructures, such as buildings and cities, accessible over the Internet. The global networking infrastructure supporting today's IoT applications predominantly relies on the TCP/IP protocol suite. The low end of the IoT spectrum, commonly referred to as the "Things" side, is characterized by battery-powered devices with constrained resources, featuring CPUs operating at frequencies ranging from tens to hundreds of megahertz and memory capacities spanning tens to hundreds of kilobytes. These devices are often mobile and possess limited computational capabilities. The interconnection of such resource-constrained devices is frequently achieved through Low-power and Lossy Networks (LLNs). LLNs facilitate communication with low data rates, typically in the range of tens to hundreds of kilobits per second, payload sizes spanning tens to hundreds of bytes, and communication ranges extending from tens to hundreds of meters. Remarkably, some low-power devices exhibit battery lifetimes extending over multiple years. LLNs predominantly leverage wireless communication technologies, often based on the IEEE 802.15.4 standard [4], which have been developed to address the limitations of resource-constrained devices.

A typical IoT system comprises several key components arranged in a multi-hop structure to facilitate efficient communication and data transfer, as depicted in Figure 2.1. IoT nodes are dispersed throughout the network, often equipped with various sensors, and operate on low power to conserve energy to gather environmental data such as humidity, temperature, and light intensity. Moreover, some nodes are also equipped with actuators that are responsible for executing actions based on the data gathered by the sensors. The actuators may control devices such as valves, switches, or motors, enabling automated responses to environmental changes or user commands [55]. The nodes communicate through wireless links and can extend the network's coverage and ensure reliable communication between distant nodes through packet routing, enhancing network robustness and resilience to connectivity disruptions.

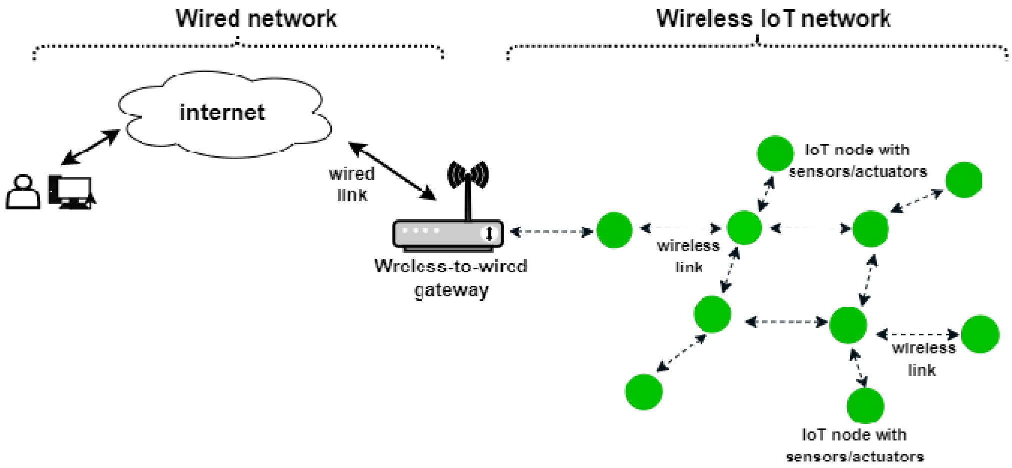


Figure 2.1: An IoT system consisting of a wireless network connected to the Internet by a wireless-to-wired gateway.

At the higher level of the network hierarchy is the gateway node, also known as the sink node. The gateway node serves as a bridge between the wireless IoT network and external wired networks, such as the Internet or local area networks. The sink node aggregates data from sensor nodes, processes it, and forwards relevant information to the cloud or other network services for storage and analysis. Lastly, the cloud plays a pivotal role in the IoT system, serving as a centralized repository for data storage, processing, and analysis. The cloud infrastructure provides scalable resources for handling large volumes of IoT data, enabling real-time monitoring, predictive analytics, and decision-making.

2.2.1 IoT applications

IoT applications retrieve data from sensor nodes, employing it for decision-making and analytics using machine and deep learning techniques, and may also manage other devices like actuators. Figure 2.2 illustrates common examples of IoT applications [55-58]. These include (but are not limited to):

Smart homes: Fueled by the IoT, smart homes have emerged as one of the most prominent and rapidly growing applications of this transformative technology. These homes leverage a network of interconnected devices, including sensors and actuators, to automate, monitor, and control various aspects of the living environment. From adjusting thermostats and optimizing energy consumption to receiving alerts for potential security breaches and remotely locking doors, smart home technology offers a wide range of convenience, security, and comfort benefits. Product offerings within the smart home market are diverse and constantly evolving, encompassing everything from intelligent lighting systems and smart appliances to interactive TVs and voice-controlled assistants. This diversity caters to a wide range of needs and preferences, making smart homes increasingly accessible and appealing to a broader audience.

Smart factories: Revolutionizing the industrial landscape, smart factories are production facilities integrated with sensors, actuators, and other connected devices. This network of "smart" equipment aims to optimize and automate industrial processes, enhancing efficiency, reliability, and safety. By minimizing human error and enabling real-time data analysis, smart factories achieve this through various applications. For instance, sensors monitor vibration levels in pumps, fuse, and lighting status, and even detect fallen workers, triggering corrective actions and preventing downtime. These capabilities translate to improved production quality, reduced costs, and enhanced worker safety.

Smart transportation: Representing a revolutionary shift towards energy efficiency, environment protection, and sustainability, smart transportation systems are poised to define the future of mobility. Integrating modern technologies and data-driven management strategies will completely transform our interaction with vehicles and transport infrastructure. IoT devices like sensors embedded in vehicles can play a crucial role: they enable features like collision avoidance and anti-skidding, significantly enhancing safety. However, the benefits extend far beyond individual vehicles. Smart transportation systems employ real-time data to improve traffic flow, dynamically adjust traffic signals, and even implement congestion pricing, effectively reducing traffic jams and emissions. This not only saves commuters time and fuel but also contributes to a cleaner and healthier environment.

Environmental monitoring: IoT deployments are instrumental in tracking environmental conditions and biodiversity. Deployed in diverse environments such as forests, wildlife areas, and marine habitats, IoT sensors monitor parameters such as temperature, humidity, air quality, and wildlife behavior. In forest environments, IoT devices strategically track endangered species, providing valuable insights into migration patterns, breeding behaviors, and potential threats to biodiversity. Real-time data collected by IoT sensors empowers conservationists with actionable information, guiding strategies for ecosystem preservation and management. Additionally, IoT technologies are employed to combat illegal activities in protected areas, leveraging motion detection sensors to detect unauthorized intrusions. Prompt alerts generated by IoT devices facilitate rapid response efforts, bolstering conservation initiatives and safeguarding natural habitats from illicit activities.

Infrastructure monitoring: Infrastructure monitoring is a crucial application of the Internet of Things (IoT), focusing on the surveillance of critical structures such as bridges and tunnels. IoT devices equipped with sensors detect variations in temperature, vibrations, and material strain. Continuous monitoring facilitates the early detection of potential issues, minimizing unexpected failures and reducing repair costs. IoT creates interconnected sensor networks, offering a comprehensive perspective that supports informed decision-making. Immediate alerts enable timely maintenance interventions, enhancing the resilience of infrastructure against environmental challenges. The integration of smart technologies with IoT significantly improves structural safety and reliability.

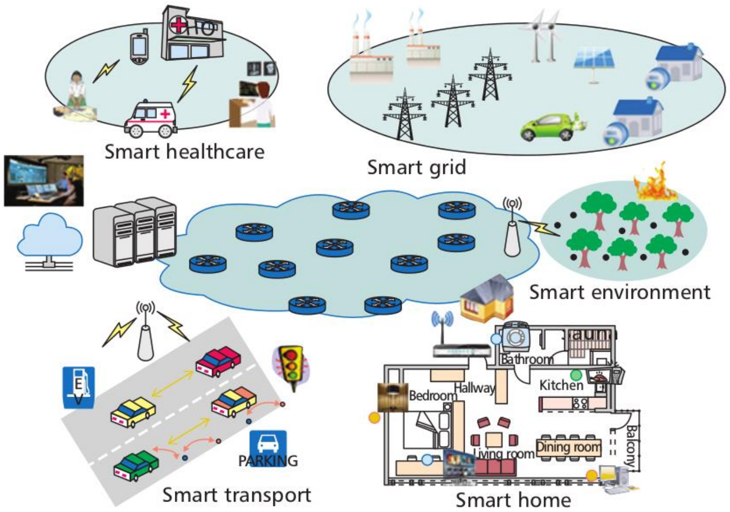


Figure 2.2: Examples of IoT applications [59].

Smart healthcare: Integrating IoT in smart health is expected to transform healthcare delivery, patient monitoring, diagnostics, and treatment. IoT-enabled devices, such as implantable monitors and wearable sensors, continuously gather and transmit crucial health data like temperature, blood pressure, glucose levels, and physical activity. This real-time data collection supports personalized healthcare, facilitating the early identification of health issues and prompt medical interventions. Moreover, IoT facilitates remote patient monitoring, decreasing the necessity for frequent hospital visits and aiding healthcare providers in effectively managing chronic conditions. Combining IoT with artificial intelligence enhances predictive healthcare, enabling the identification of potential health risks before they escalate into serious conditions. Smart health systems also boost the efficiency of healthcare operations by automating administrative tasks, streamlining patient records, and optimizing resource management.

Smart agriculture: This involves utilizing IoT devices like sensors in farming to minimize production costs and optimize agricultural output. These devices monitor parameters such as soil and water quality, enabling farmers to adjust their strategies, such as pesticide usage. Projections suggest that by 2050, smart agriculture through IoT could increase food production by 70% [60]. Precision agriculture solutions employ IoT systems to enhance productivity through informed decision-making. For instance, farmers utilize IoT devices to gather data on factors like crop humidity, temperature, and livestock movements. This data is then analyzed using machine and deep learning algorithms to forecast potential diseases or weather events like frost, facilitating proactive decision-making.

2.2.2 Challenges of IoT

The rapid growth and diverse applications of the Internet of Things (IoT) are accompanied by a unique set of challenges. These challenges arise from the resource-constrained nature of IoT devices, the dynamic and complex nature of IoT deployments, and the limitations of existing networking protocols [6, 9, 10, 13, 55]. We discuss below these key challenges:

Deployments in constrained environments: Deployments in constrained environments present significant challenges for IoT applications, as they often rely on resource-limited devices. These challenges stem from constraints in processing power, storage capacity, communication capabilities, and battery power. Constrained devices typically face limitations in processing capabilities, impacting their ability to execute complex algorithms or handle large data volumes efficiently. Consequently, this limitation may result in delays in data processing, slower response times, and an overall reduction in system performance. Furthermore, the limited storage capacity of these devices poses challenges in storing and managing extensive datasets or historical data, potentially hindering critical data retention for analysis and decision-making purposes.

In addition to processing and storage constraints, limitations in communication capabilities also arise, characterized by restricted bandwidth, limited range, or unreliable connectivity. These communication challenges can lead to data transmission bottlenecks, increased latency, and the risk of data loss or corruption during transmission. Moreover, many constrained devices rely on battery power, introducing further challenges related to energy consumption and battery life. To address these challenges, energy-efficient communication protocols, optimized data transmission methods, and effective power management strategies are crucial to prolong battery life and ensure uninterrupted device operation. Overcoming these constraints is vital for maximizing the performance, reliability, and longevity of IoT deployments in constrained environments.

Complex and dynamic network topologies: Complex and dynamic network topologies are inherent to IoT deployments, characterized by a multitude of heterogeneous wireless devices that frequently change network topology. These changes may occur due to device mobility, reconfiguration, or even device failures, leading to a dynamic and ever-evolving network environment. Effectively managing these dynamic topologies poses significant challenges for routing protocols, resource allocation algorithms, and network optimization techniques. The dynamic nature of IoT networks necessitates scalable and self-organizing solutions to ensure reliable and efficient data delivery in such dynamic environments. Scalability is crucial to accommodate the growing number of devices and their interactions, while self-organizing capabilities empower networks to adapt autonomously to topology changes, improving resilience and optimizing resource utilization.

Efficient content-location mapping: Efficient content-location mapping is a critical challenge faced by IoT applications, particularly those that rely on real-time access to data based on location. The dynamic nature of IoT environments, characterized by frequent changes in device locations, evolving network configurations, and the potential for data mobility, complicates the task of accurately mapping content to its respective location. This challenge becomes even more pronounced in large-scale IoT deployments, emphasizing the need for efficient content-location mapping techniques. Timely and accurate data retrieval hinges on the development of sophisticated mapping strategies that can adapt to the dynamic nature of IoT environments, ensuring that data remains accessible and relevant despite constant changes in device positions and network structures.

Inadequacy of TCP/IP protocol stack: The inadequacy of the TCP/IP protocol stack becomes glaringly evident when applied to the dynamic and resource-constrained environments characteristic of IoT networks. Designed primarily for the static wired internet, the TCP/IP protocol stack encounters significant challenges in adapting to the unique demands of IoT applications. These challenges include the frequent mobility of IoT devices, the limited bandwidth available in wireless communication channels, and the stringent energy constraints prevalent in LLNs. Additionally, traditional IP-based routing mechanisms and point-to-point transmissions struggle to efficiently manage the dynamic topology changes, intermittent connectivity, and fluctuating network conditions inherent in IoT deployments.

These shortcomings highlight the imperative for innovative networking paradigms that can effectively overcome these challenges. New protocols and architectures are required to adjust routing paths dynamically, optimize energy consumption, prioritize critical data transmissions, and seamlessly integrate with diverse IoT devices and communication technologies. By embracing these new networking paradigms, IoT networks can achieve enhanced performance, scalability, and resilience, thus unlocking the full potential of IoT technologies across various domains.

Secure data exchange: Secure data exchange is paramount in IoT networks due to the sensitive nature of the data being collected and transmitted. Robust security measures are essential to safeguard data confidentiality, integrity, and availability. This involves addressing vulnerabilities in existing protocols, implementing robust encryption and authentication mechanisms, and establishing secure access control protocols. Furthermore, the dynamic nature of IoT networks necessitates flexible and adaptable security solutions that can evolve alongside the network itself. This adaptability ensures that security measures remain effective even as the network topology, device configurations, and communication patterns change over time.

However, the limited processing power of IoT devices can pose significant challenges to implementing comprehensive security measures. For instance, constrained processing capabilities may restrict the use of complex cryptographic algorithms, making it challenging to ensure robust encryption and authentication mechanisms. This limitation can create vulnerabilities that malicious actors may exploit to gain unauthorized access to sensitive data or compromise communication channels. To address these challenges, adequate security measures in IoT networks must consider these constraints and develop tailored solutions that balance security requirements with resource limitations.

2.3 Low power & lossy networks

LLNs are a crucial component of the IoT landscape, facilitating communication among resource-constrained devices in environments with limited power and connectivity [61]. LLNs exhibit several key features that differentiate them from traditional wired or high-bandwidth wireless networks such as WiFi [22]. These features include:

Low power consumption: The most defining characteristic of LLNs is their low power consumption. Devices in these networks are typically battery-powered or energy-harvesting, necessitating energy-efficient communication protocols and operation modes to extend battery life and ensure prolonged network operation without frequent battery replacements or recharging.

Lossy communication links: LLNs often operate in environments where communication links are prone to packet loss, latency, and variable quality due to factors such as distance, interference, and environmental conditions. This lossy nature of communication necessitates robust error-handling mechanisms and adaptive routing protocols to ensure reliable data transmission despite potential packet loss.

Resource constraints: Devices in LLNs are constrained in terms of processing power, memory, and storage capacity. These resource limitations impose constraints on the complexity of communication protocols, routing algorithms, and data processing capabilities of LLN devices. Efficient resource utilization is essential to accommodate the functionality required for IoT applications while operating within the constraints of LLNs.

Topology dynamics: LLNs often exhibit dynamic network topologies due to device mobility, intermittent connectivity, and variable link quality. Devices may join or leave the network, and network topology may change frequently, requiring adaptive routing protocols capable of dynamically adjusting to topology changes and optimizing data transmission paths in real-time.

Low data rates: LLNs typically operate at low data rates compared to high-bandwidth wireless networks. This low data rate is sufficient for many IoT applications that involve periodic transmission of small data packets, such as sensor data or control commands. However, it necessitates efficiently utilizing available bandwidth and optimizing communication protocols to minimize overhead and maximize throughput.

Multi-hop communication: LLNs typically operate at low data rates compared to high-bandwidth wireless networks. This low data rate is sufficient for many IoT applications that involve periodic transmission of small data packets, such as sensor data or control commands. However, it necessitates efficiently utilizing available bandwidth and optimizing communication protocols to minimize overhead and maximize throughput.

Understanding these characteristics is essential for effectively designing and deploying IoT solutions in LLNs. By leveraging the unique properties of LLNs and adapting communication protocols and algorithms to suit these characteristics, it is possible to build resilient, energy-efficient, and scalable IoT systems capable of operating in diverse real-world environments.

2.3.1 Communication technologies in LLNs

The IEEE 802 Standard encompasses a diverse range of networking standards, including IEEE 802.11, widely known as WiFi [22], IEEE 802.15.4 [4], represented by ZigBee [62], and IEEE 802.15.1 [63], typified by Bluetooth, among others. While WiFi has proven effective for Wireless Local Area Networks (WLANs) due to its ample bandwidth, it falls short of meeting the specific requirements of Internet of Things (IoT) local networks. In IoT scenarios, priorities shift towards low bandwidth, low power consumption, scalability for accommodating large numbers of nodes, and support for long-range communication. This is where LLNs come into play. LLNs are specifically designed to cater to the needs of IoT devices, which often operate in resource-constrained environments. In contrast to WiFi's high energy consumption and cost, LLNs leverage specialized wireless technologies that support scalability and offer low-power operations and low communication range for extended battery lifetime, making them ideal for IoT deployments. While Table 2.1 summarizes the main technologies for LLNs in terms of frequency, data rate, communication range, and cost, a brief description of each technology is provided below.

IEEE 802.15.4 [4]: Operating within the 2.4 GHz ISM band, IEEE 802.15.4 is specifically designed for low-rate wireless personal area networks (LR-WPANs). This standard employs 27 non-overlapping channels, with 16 allocated in the 2.4 GHz band and 11 in the sub-GHz bands, reducing interference and efficient spectrum utilization. The 2.4 GHz band offers a maximum data rate of 250 kbps, catering to applications with low data transfer requirements. Each frame typically has a maximum transmission unit (MTU) of 127 bytes and is protected by a 16-bit cyclic redundancy check (CRC), ensuring data integrity during transmission.

One of the key advantages of IEEE 802.15.4 is its simplicity and low power consumption, making it ideal for scenarios where intermittent data transmission is common. This technology supports various network topologies, including star, mesh, and cluster trees, offering flexibility to adapt to different application requirements. The star topology is suitable for point-to-point or point-to-multipoint communication, while the mesh topology enables decentralized communication among multiple nodes, enhancing reliability and fault tolerance. Cluster trees are well-suited for hierarchical network structures, facilitating efficient data aggregation and management. Overall, IEEE 802.15.4 is well-suited for applications that require short-range communication with low power consumption, such as home automation, industrial monitoring, and wearable devices.

Bluetooth Low Energy (BLE) [64]: is based on the IEEE 802.15.1 standard [63] and functions in the 2.4 GHz ISM band. BLE focuses on low-power, low-data-rate applications, offering sufficient bandwidth for short-burst data transmissions. BLE employs frequency hopping over 37 channels for bidirectional communication and 3 for unidirectional advertising, with a bit rate of 1 Mbps. In Bluetooth 4.0, the link-layer MTU is 27 bytes, increased to 251 bytes in Bluetooth 4.2. With a moderate range suitable for personal area networks, BLE excels in ultra-low power consumption, making it ideal for devices requiring energy efficiency and small, coin-cell batteries. Commonly using star topologies with a master node orchestrating bidirectional communication with one or several slave nodes. BLE is ideal for situations where devices require brief communication in a point-to-point mode.

Long Range Wide Area Network (**LoRaWAN) [65, 66]:** Developed for long-range communication, LoRaWAN operates primarily in the sub-GHz frequency bands, including 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia. These frequency bands offer excellent propagation characteristics, allowing LoRaWAN to achieve extended communication ranges even in challenging environments. In terms of data rate, LoRaWAN typically supports low to moderate bandwidth, ranging from a few hundred bits per second (bps) to several kilobits per second (kbps), depending on factors such as spreading factor and channel bandwidth settings. For example, devices can achieve data rates ranging from 0.3 to 50 kbps. One of the key features of LoRaWAN is its long communication range, which can span several kilometers in rural areas and up to a few hundred meters in urban environments. This extended range makes LoRaWAN well-suited for applications where devices are dispersed over large geographical areas, such as smart agriculture, environmental monitoring, and asset tracking.

(NB-IoT) [67, 68]: NB-IoT operates within licensed spectrum bands, typically utilizing frequencies such as 800 MHz, 900 MHz, or 1800 MHz, depending on regional regulations and operator deployments. These licensed bands ensure reliable and interference-free communication, especially in dense urban environments where cellular networks are prevalent. In terms of data rate, NB-IoT offers relatively low bandwidth compared to traditional cellular technologies, typically ranging from a few kilobits per second (kbps) to a maximum of around 250 kbps. While this bandwidth may seem limited compared to broadband cellular technologies, it is well-suited for many IoT applications that prioritize energy efficiency and long-term connectivity over high data throughput. Moreover, the communication range of NB-IoT can reach several kilometers in ideal conditions. This extended range enables NB-IoT devices to communicate reliably over large geographic areas, making it suitable for applications such as smart metering, asset tracking, and environmental monitoring. NB-IoT typically utilizes cellular network topologies, leveraging existing infrastructure deployed by mobile operators.

Table 2.1: Wireless technologies for low power and lossy networks

Technology	Frequency	Data Rate	Typical range	Power Usage	Cost
IEEE 802.15.4 [4]	sub-GHz, 2.4 Ghz	250 Kbps	10-50 m	Low	Low
BLE [64]	2.4 Ghz	1, 2, 3 Mbps	30 m	Low	Low
LoRaWan [65, 66]	sub-GHz	< 50 Kbps	2-10 Km	Low	Medium
NB-IoT [67, 68]	Cellular Bands	0.1-1 Mbps	Several Km	Medium	High

2.3.2 Adopting IEEE 802.15.4 for LLNs

As stated above, to support IoT applications, LLNs should have an efficient and adept power management strategy, cost-effectiveness in production, and the ability to seamlessly support a multitude of (mobile) nodes. In contrast, substantial bandwidth is not a primary requirement for many IoT environments. As discussed above, several wireless technologies have emerged to address these requirements.

LoRaWAN and NB-IoT may not be ideal for supporting LLNs due to several limitations. These technologies operate in licensed spectrum bands, which can restrict accessibility and deployment flexibility. Additionally, their reliance on cellular infrastructure and long-range communication capabilities may introduce complexities and scalability challenges in LLN deployments. Furthermore, the relatively higher energy consumption of LoRaWAN and NB-IoT devices could pose challenges in achieving prolonged battery life in power-constrained LLN environments. Thus, while LoRaWAN and NB-IoT offer extended coverage, their suitability for LLNs in IoT applications is limited by factors such as spectrum availability, bandwidth constraints, network architecture, and power efficiency considerations. Consequently, when considering wireless technologies for LLNs, Bluetooth Low Energy (BLE) and IEEE 802.15.4 stand out as notable contenders.

BLE is based on IEEE 802.15.1 and offers several advantages, including widespread adoption and compatibility with a diverse array of devices. However, its optimization for short-range personal area networks is a key consideration. BLE primarily supports star and point-to-point topologies, making it more suitable for scenarios where devices communicate directly with a central hub or with each other on a one-to-one basis. While BLE excels in such environments, its efficacy diminishes in larger-scale mesh networks commonly encountered in LLN deployments. Mesh networks, characterized by interconnected nodes that relay data between each other, present a more complex communication environment, challenging BLE's ability to maintain reliable routing, especially in scenarios requiring extended communication paths, such as in large industrial facilities or outdoor environments.

In contrast, IEEE 802.15.4, which was originally designed for low-power, low-data-rate wireless communications, emerges as a preferred choice for LLNs. Its energy-efficient protocols and operation modes are well-aligned with the power-saving requirements of IoT devices, facilitating prolonged battery life and enhanced network longevity. Furthermore, IEEE 802.15.4 offers robust support for mesh networking, a critical feature for LLNs operating in dynamic and challenging environments. Mesh networking enables resilient communication across interconnected nodes, ensuring reliable data transmission even in the face of node failures or network disruptions. Additionally, IEEE 802.15.4 provides greater flexibility concerning communication range and data rates, facilitating scalability and adaptability to diverse IoT deployment scenarios.

Therefore, the selection of IEEE 802.15.4 over BLE in LLNs is driven by its superior alignment with the specific requirements and challenges of low-power IoT networks. Its support for mesh multi-hop networking, energy efficiency, and scalability across various deployment scenarios makes it an ideal choice for enabling robust and resilient communication within LLNs.

2.3.3 The medium access control in IEEE 802.15.4

The IEEE 802.15.4 standard [4] specifies the lower two protocol layers of the OSI model: the Physical (PHY) layer and the Media Access Control (MAC) layer, as depicted in Figure 2.3. In IEEE 802.15.4, multiple options are available, depending on the desired trade-off between data rate, range, and power consumption. The standard supports various network topologies, allowing for flexible deployment options. Power-saving mechanisms are employed to permit devices to enter sleep mode to conserve battery life while maintaining network connectivity.

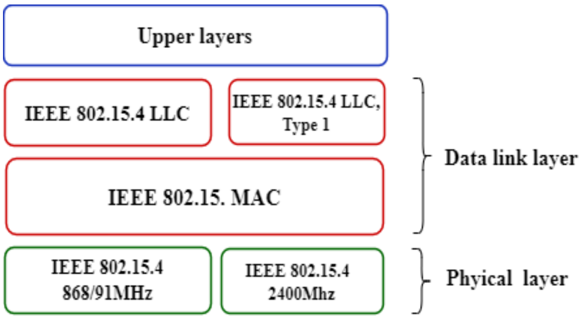


Figure 2.3: The protocol layers specified in the IEEE 802.15.4 standard.

The PHY layer defines the characteristics of the wireless signal used for communication, whereas the MAC layer manages access to the shared wireless medium and provides reliable data delivery. It uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithms to regulate access to the medium and thus reduces packet collisions by requiring devices to sense the channel before transmitting.

The IEEE 802.15.4 standard [4] defines two versions of the CSMA/CA algorithm: *slotted* and *unslotted*. Most studies on NDN over IEEE 802.15.4 have assumed the unslotted version as the default implementation [16-20]. Contrary to its slotted counterpart, unslotted CSMA/CA is a contention-based protocol that requires no synchronization between nodes. A given node puts all packets in a FIFO queue. Before initiating a transmission, a node checks the availability of the wireless channel. If the channel is occupied, the node backs off for a random period and initiates a retransmission attempt after the backoff period expires. If a transmission is unsuccessful, the node will make a predetermined number of retransmission attempts before ultimately abandoning the packet.

Adopting the technical terms specified in the IEEE 802.15.4 standard [4], a given node keeps track of the two variables: NB and BE. The former is the number of times the node has performed a backoff while attempting the current transmission. NB is set to 0 before every new packet transmission. BE is the backoff exponent and is related to the number of backoff periods a node must wait before re-sensing the channel. The CSMA/CA algorithm employs time units called backoff periods, measured by *aUnitBackoffPeriod* symbols [4]. The parameters affecting the random backoff period are *macMinBE* and *macMaxBE*, which are the minimum and maximum values of BE, respectively, while *macMaxCSMABackoff* is the maximum value of NB. The parameters must satisfy the following conditions: $macMinBE \leq BE \leq macMaxBE$ and $0 \leq NB \leq macMaxCSMABackoff$ [4].

Figure 2.4 illustrates the operations of the unslotted CSMA/CA algorithm to transmit a new frame. In Step 1, *NB* and *BE* are initialized to 0 and *macMinBE*, respectively. In Step 2, the MAC sublayer delays for a random number of complete backoff periods in the range 0 to $2^{BE}-1$, and in Step 3, it requests the PHY sublayer to perform a Clear Channel Assessment (CCA). If the channel is busy in Step 4, the MAC sublayer increases *NB* and *BE* by one, ensuring that *BE* is not higher than *macMaxBE*. If the value of *NB* is less than or equal to *macMaxCSMABackoff*, the algorithm must return to Step 2. Otherwise, the MAC sublayer drops the frame and terminates. If the channel is idle, in Step 5, the MAC sublayer starts immediately the transmission of the frame. Transmission starts when the backoff counter reaches zero. A collision occurs when the counters of two or more nodes transmit frames simultaneously. It is worth noting that in the unslotted CSMA/CA of the IEEE 802.15.4 standard with the default settings, the parameters are set as follows: *macMinBE*= 3, *macMaxBE*= 5, ma*MaxCSMABackoff*= 4 [4].

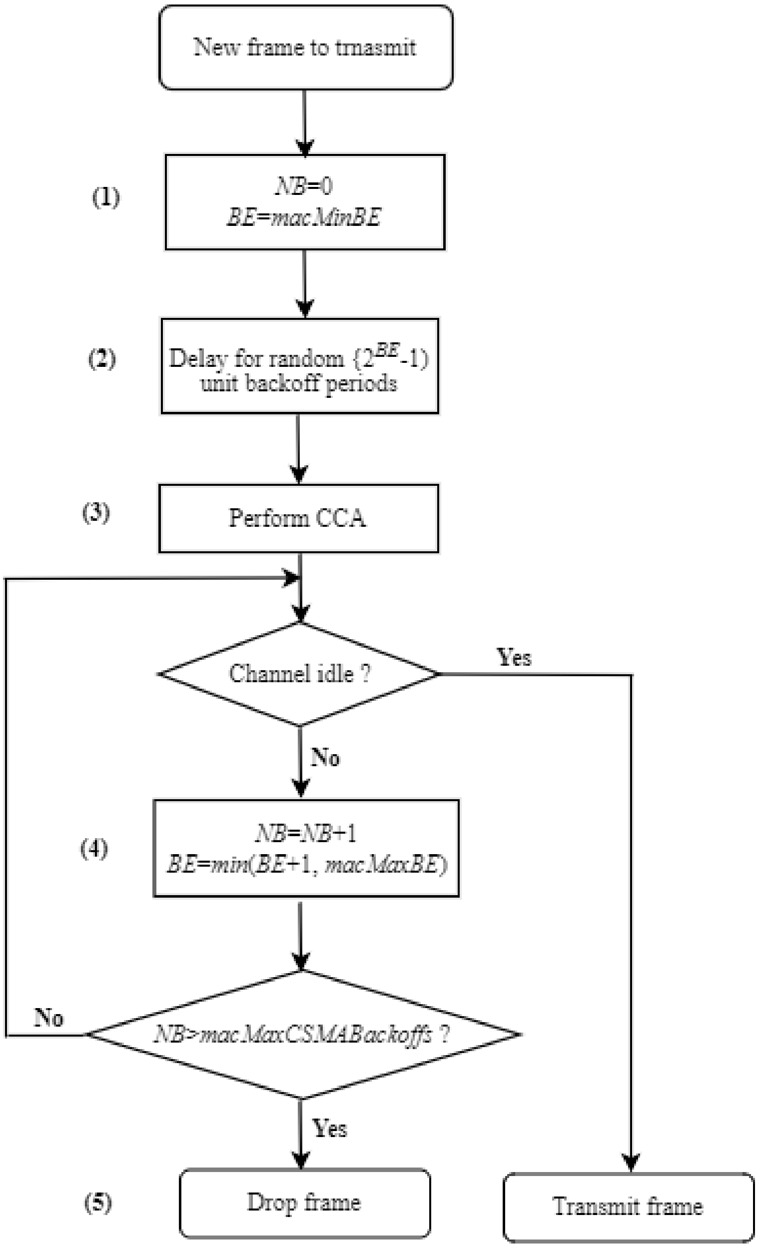


Figure 2.4: The operations of the unslotted CSMA/CA algorithm in the IEEE 802.15.4 standard.

2.4 Summary

This chapter has provided a background on the Internet of Things (IoT), elucidating its wide-ranging applications across various economic and societal sectors. Central to our discussion has been the critical role of Low-power and Lossy Networks (LLNs) in facilitating connectivity among a myriad of interconnected devices, a typical feature of numerous IoT applications.

This chapter has provided a background on the Internet of Things (IoT), and shed light on its diverse applications spanning various economic and societal sectors. Central to our discussion has been the pivotal role of Low-power and Lossy Networks (LLNs) in enabling seamless connectivity among a multitude of interconnected devices, a characteristic hallmark of numerous IoT applications.

Our analysis of wireless technologies tailored for LLNs has provided valuable insights into their unique characteristics and inherent trade-offs. Following a careful examination of these technologies, we have selected the IEEE 802.15.4 communication technology to explore their suitability for new emerging networking paradigms, such as Named Data Networking (NDN). This selection is underpinned by its advantageous attributes, including low power consumption, scalability, and support for multi-hop communication, all of which are crucial for ensuring effective IoT deployments in practical scenarios.

3. Named Data Networking

3.1 Introduction

The traditional IP networks forming the backbone of the Internet were originally designed in the 1970s and were built on the fundamental design principle of end-to-end communication, heavily influenced by the old telephone system. This gave rise to the TCP/IP protocol suite in the 1980s, which became the backbone of global connectivity, facilitating communication by establishing end-to-end connections between hosts and enabling application development on top of the TCP protocols [7].

IP networks operate by first establishing a connection between two hosts; i.e., usually between a client and server. To achieve this, the network needs to know the IP address of the source and destination hosts. The IP address serves as the unique identifier for each host in the network, allowing packets to be routed correctly. When a connection is initiated, the TCP protocol suite ensures reliable and orderly data transmission by segmenting data into packets, assigning sequence numbers to each packet, and managing acknowledgments and retransmissions to guarantee data integrity and delivery. The TCP/IP communication framework has played a pivotal role in shaping modern networking and internet communication, laying the foundation for the interconnected digital world we rely on today.

However, the landscape of communication has been drastically transformed since the early days [69, 70]. For example, users nowadays care about the contents themselves rather than the hosts that hold the contents or the details of their IP addresses. This shift is exemplified in everyday experiences; for instance, when making a query in the Google search engine, users are interested in the content of the responses and not which server has replied. Additionally, today's networks embody new communication paradigms that prioritize content sharing and retrieval, embrace broadcast/multicast communication, accommodate mobility, and cater to the burgeoning Internet of Things (IoT) ecosystem alongside cloud and edge computing [1, 2, 3]. These modern communication requirements have rendered IP networks inadequate and inefficient [5, 6, 9, 10]. This has spurred the emergence of Named Data Networking (NDN) [15, 16], which is one of the innovative approaches of Information Centric Networks (ICN) [11, 12, 13], designed to address the shortcomings of traditional IP-based networks. The new networking paradigm prioritizes content by its name rather than its location, fundamentally altering how data is accessed, retrieved, and transmitted across networks.

By focusing on data-centric principles, NDN aims to improve network efficiency, scalability, and security while better aligning with the communication needs of modern and emerging applications, such as those in the IoT domain. The objective of this chapter is to provide an overview of the new NDN paradigm, its fundamental operations, and how it can offer support for content sharing and mobility for emerging IoT applications.

The rest of this chapter is structured as follows. Section 3.2 introduces the ICN framework, while Section 3.3 presents NDN and its solutions to meet the IoT challenges. Sections 3.4 and 3.5 describe the different types of packets and data structures used in NDN, respectively. This is followed by a discussion on the interest forwarding process in NDN in Section 3.6 and its deployment over LLNs in Section 3.7. Finally, Section 3.8 summarizes the key points discussed in this chapter.

3.2 Information centric networks

The continually expanding digital terrain, characterized by a relentless increase in both content creation and consumption, poses a challenge to conventional IP networks. In response to the evolving needs of contemporary communication ecosystems, the Information-Centric Networking (ICN) paradigm [11, 12, 13] has emerged as a compelling solution. In the present digital landscape, where the emphasis has shifted from host-centric interactions to the widespread sharing and retrieval of digital content, ICNs offer a transformative framework. This framework suggests a departure from established host-centric communication models by prioritizing information as the primary entity of interest. In contrast to traditional IP networks, where data retrieval necessitates the knowledge of specific hosts or endpoints, ICNs advocate for a shift toward content-centric communication. This transition has significant implications for various applications, ranging from efficient content delivery in modern networks to innovative strategies for securing and optimizing data dissemination. At the core of ICNs is the fundamental tenet of decoupling information from its originating source, fostering a network environment where content itself becomes the central focus of communication.

In the past few years, several ICN architectures, including Named Data Networking (NDN) [16, 21], Data-Oriented Network Architecture [71, 72], Scalable and Adaptive Internet Solutions (SAIL) [73], and Network of Information (NetInf) [74], have been proposed. Despite having distinct protocol designs, they are united by common principles, encompassing content abstraction, content-centric naming and security, and a connectionless receiver-driven communication model. These shared principles underlie the two primary features found in all ICN architectures: name-based networking operations and built-in in-network caching. In what follows, we will briefly describe the shared principles of ICN architectures [11, 12, 13].

Content abstraction: ICN architectures function based on Named Data Objects (NDOs), which can encompass diverse entities like web pages, photos, or sensor data—objects that computers can store and access. NDOs possess names that remain consistent throughout the network, enabling various copies, such as those in different caches, to equally fulfill retrieval requests. NDOs be divided into packets or may exist as full objects depending on the ICN architecture.

Content-centric naming and security: ICN requires globally unique names to identify NDOs. Architectures can adopt hierarchical, flat, or attribute-value names. Hierarchical names resemble URIlike names of variable length, while flat names take the form P:L, with P being the ciphered hash of the content owner's public key and L a unique label identifying a specific content item. Attribute-value naming involves each attribute having a name, type, and set of possible values.

In ICN, content is uniquely identified and self-authenticated, irrespective of its location in the network. To ensure authenticity verification independent of content location, ICN establishes a binding between content, its name, and the creating entity. The content source signs the content, its name, and its origin just before injecting the content object into the network. Users verify content legitimacy by checking the signature, and a content-based security mechanism enables protection and trust to be carried within the packet itself, eliminating the need for secure communication channels as in IP networks.

Connectionless receiver-driven communication model: Connectionless interaction in ICN eliminates the need for assigning individual addresses to network devices. In this model, users acquire data by sending requests to the network for specific content identified by its name. This request mechanism resembles posing a query in the form of "Is there any content matching this name available?" and the network's response constitutes the data retrieval process. Therefore, data retrieval in ICN follows a receiver-driven approach, involving two main phases: (i) initiating and transmitting a request from the consumer to either the producer or an intermediate cache, and (ii) delivering the requested content back to the requester. It is important to highlight that while no specific ICN architecture has been tailored for the Internet of Things (IoT), ongoing research in ICN presents an opportunity to design forthcoming architectures with IoT requirements in consideration.

3.3 Named Data Networking

Named Data Networking (NDN) is among the most popular implementations of ICN [11, 12, 13]. NDN was initiated in September 2010 and funded by the National Science Foundation (NSF) as part of its Future Internet Architectures (FIA) program [75, 76]. NDN inherits the TCP/IP architecture hourglass shape but substitutes the end-to-end data delivery model with a receiver-driven data retrieval model at the thin waist level. As depicted in Figure 3.1, the IP layer serves as the central point through which all IP packets exchanged between hosts must pass, representing the "thin waist" of the traditional networking architecture. In contrast, within the NDN paradigm, the thin waist shifts to the NDN layer handling content chunks (or packets), symbolizing a fundamental change in how data retrieval and communication occur within the network. This novel networking architecture initiates a transition in the communication paradigm, moving away from a location-centric approach (focusing on "where") to a data-centric one (focused on "what"). In NDN, data is retrieved directly at the network layer by decoupling the sender from the receiver. This is achieved by utilizing application data names instead of host addresses. The fundamental vision of NDN is underpinned by several core principles outlined below [15-17, 75, 76].

Universality: NDN aims to serve as a universal network protocol suitable for diverse applications and network environments. Unlike traditional IP-based networks, where specific protocols may be tailored to particular applications, NDN strives for a unified approach applicable across the entire network spectrum.

Receiver-driven (or pull-based model): In the NDN framework, content retrieval involves a receiver initiating a request for specific content, to which a data source responds with the corresponding data. Notably, data transmission occurs only when there is a request from a receiver; otherwise, no data is transmitted across the network.

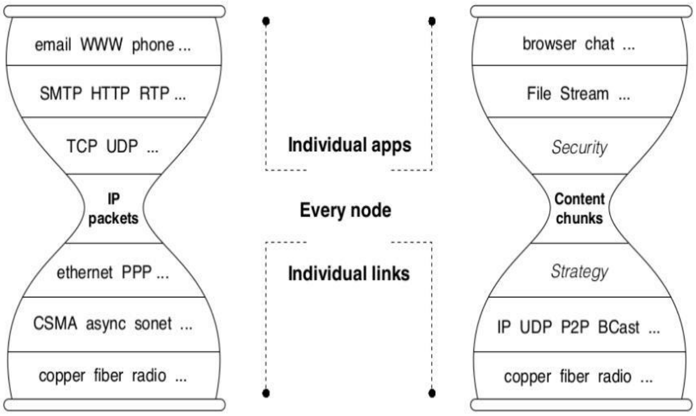


Figure 3.1: The hourglass depicting the thin waist in the TCP/IP and NDN architecture [76].

Data-centricity and data immutability: In NDN, the focus shifts from communication that is based on host addresses to retrieving data based on content. Data packets are uniquely named and immutable, meaning that once published, their content remains unchanged. Requests for data are made through "interest packets", as will be detailed below, which specify the desired content rather than specific host addresses.

Hierarchical naming: NDN employs hierarchical naming schemes for packets, enabling efficient demultiplexing and providing structured context for content (or data) retrieval. This hierarchical approach facilitates scalable and organized data dissemination and retrieval within the network.

In-network name discovery: NDN supports the concept of in-network name discovery, allowing the use of partial or incomplete names to retrieve data packets. This feature enhances flexibility and efficiency in data retrieval, especially in scenarios where precise content names may not be known in advance.

In-network caching: Unlike traditional IP-based networks where data is fetched from specific hosts, NDN introduces the idea of caching content directly within the network infrastructure. This means that network nodes (e.g. routers) can store frequently accessed data packets, creating a distributed caching system across the network. When a consumer requests a piece of data, NDN's forwarding process includes querying the network for cached copies before reaching the original producer of the data. If a cached copy is found along the path, it can be quickly retrieved and delivered to the consumer, reducing latency and conserving bandwidth. In-network caching optimizes data delivery, enhances content availability, and promotes network efficiency by leveraging the distributed storage capabilities of network nodes.

One-request-one-response: NDN maintains a balance in data flow between request and data packets over each link in the network. Specifically, each request sent over a link should result in the transmission of no more than one corresponding data packet. This mechanism helps regulate network traffic and ensures fair resource utilization.

Securing data directly: Securing data directly is a foundational principle in NDN, where data packets themselves are designed to possess inherent security features. This approach stands in contrast to traditional network architectures, where security often relies heavily on securing communication channels. In NDN, each data packet is cryptographically signed, guaranteeing both data integrity and authenticity throughout its entire lifecycle, whether it is in transit across the network or stored in a cache. This robust security mechanism not only safeguards data from unauthorized modifications or tampering during transmission but also ensures that data remains trustworthy and valid even when stored in local caches.

3.3.1 NDN meeting IoT challenges

Upon encountering NDN, a common question arises regarding how to leverage its capabilities without enduring lengthy periods for the evolution of internet architecture. Nonetheless, substantial alterations are necessary in existing IP-centric networking infrastructure, protocols, and applications due to NDN's reliance on content names rather than host addresses. Moreover, persuading proponents of IP and industry stakeholders about the advantages of NDN remains challenging as long as IP solutions are good enough for current applications. Thankfully, recent years have witnessed a surge in research studies [18-21] scrutinizing the compatibility of NDN with the IoT, consequently enhancing its capabilities substantially. This surge is motivated by the realization that integrating NDN into IoT applications heralds a paradigm shift towards more efficient, scalable, and secure communication architectures. By leveraging content-based communication, in-network caching, multicast/broadcast support, and enhanced security mechanisms, NDN addresses key challenges inherent in traditional IP-based approaches, paving the way for innovative and scalable IoT solutions [18, 19, 21, 26, 75].

Elimination of IP addressing: One of the significant advantages of NDN over traditional IP networks lies in the elimination of dependencies on IP addressing. Unlike IP networks that rely on finite and hierarchical IP addressing schemes, NDN prioritizes content-based communication. This fundamental shift removes the constraints imposed by limited IP address spaces, which often require complex address management strategies, especially in large-scale IoT deployments. With NDN, devices and applications can communicate directly based on the content they seek, rather than being bound by specific IP addresses. This content-centric approach not only simplifies communication but also enhances scalability, as NDN networks can seamlessly handle a vast and dynamic range of content without the need for continuous address allocation and management overhead. As a result, NDN offers a more flexible and efficient networking paradigm for IoT environments, where the focus is on accessing and sharing content rather than managing network addresses.

Shift from host-location to content-based communication: Another fundamental advantage that (NDN) offers over IP networks, particularly for IoT applications, is its shift from host location-based communication to content-based communication. In traditional IP-based approaches, communication is directed towards specific hosts identified by their unique IP addresses. However, NDN operates on the principle of retrieving data based on its content rather than the location of the host. This paradigm shift simplifies communication protocols by eliminating the need for constant IP address tracking and management. It also enhances scalability as devices can access data directly based on what they need, without concerns about host addresses. This content-based approach is particularly beneficial in dynamic IoT environments where devices frequently change their network addresses due to mobility or network reconfiguration. By focusing on data rather than host locations, NDN provides a more flexible, efficient, and scalable framework for IoT applications, facilitating seamless data access and communication across diverse network environments.

In-network caching for asynchronous communication: NDN incorporates in-network caching mechanisms, allowing data to be stored and retrieved locally within the network. This functionality significantly supports asynchronous communication, enabling consumers and producers to interact without the necessity of being simultaneously active within the network. As a result, NDN optimizes network resources by efficiently utilizing cached data and effectively reduces latency by retrieving frequently requested content from nearby caches. This approach remains independent of the physical location of either the producer or consumer, promoting seamless data access across the network. Furthermore, the caching mechanism enhances system resilience and reliability by mitigating the potential impact of network disruptions or failures, ensuring continuous and uninterrupted data delivery in IoT environments.

Mobility support: NDN provides intrinsic support for mobility in IoT applications, marking a significant advancement over traditional networking paradigms. Unlike conventional networks that grapple with complex address changes during mobility, NDN simplifies the management of mobility by centering on content retrieval through data names rather than device locations. This strategy ensures that IoT devices can move seamlessly without interrupting data access, as content names remain constant irrespective of device location. Moreover, in-network caching can reinforce mobility support by strategically storing frequently accessed data near requesting devices. Caching not only minimizes latency but also alleviates network congestion during mobility events, optimizing overall system performance in dynamic IoT environments. Additionally, the development of efficient strategies that can enable efficient data delivery even in dynamically changing network topologies further enhances NDN’s mobility support for IoT applications.

Support for multicast and broadcast: NDN inherently supports multicast and broadcast communication paradigms, enabling multiple consumers to request the same content simultaneously. This capability is particularly advantageous in IoT scenarios where data dissemination to multiple recipients is common, such as firmware updates, sensor data distribution, or group-based control commands. By eliminating the need for individual point-to-point communication sessions, multicast and broadcast support in NDN reduces network congestion, minimizes bandwidth consumption, and enhances the scalability of IoT deployments. Additionally, this feature facilitates efficient content delivery to geographically dispersed consumers, fostering collaboration and coordination in distributed IoT applications.

Furthermore, in-network caching in NDN can play a crucial role in supporting multicast and broadcast communication. Caching frequently requested data at strategic points within the network allows for efficient retrieval and delivery of content to multiple recipients without overwhelming the network. This caching strategy not only reduces latency but also optimizes bandwidth utilization by serving content from nearby caches rather than fetching it from distant sources for each request. As a result, in-network caching enhances the reliability, scalability, and performance of multicast and broadcast communication in dynamic IoT environments.

Enhanced security: NDN offers inherent security and privacy benefits for IoT applications by incorporating cryptographic principles into its architecture. With NDN, data packets are signed by producers and verified by consumers, ensuring data integrity and authenticity throughout the communication process. Furthermore, NDN's content-centric approach inherently protects data privacy by focusing on securing the content itself rather than relying solely on secure communication channels. This design feature mitigates vulnerabilities associated with traditional network-centric security models, such as IP-based surveillance and eavesdropping attacks. As a result, NDN enhances trustworthiness and confidentiality in IoT ecosystems, making it well-suited for applications handling sensitive or critical data.

Example:

Figure 3.2 illustrates a practical IoT application that demonstrates the potential of NDN over LLNs in enabling efficient and reliable communication for remote livestock health monitoring in a smart farm environment, facilitating prompt and precise medical interventions to optimize resource utilization. The monitoring system utilizes a range of sensors such as those for blood pressure, temperature, and movement, to individually track the health, fertility, and location of each animal. The gathered data is then subjected to analysis, which serves purposes like detecting signs of illness in animals or predicting their activities accurately and promptly. Given the mobility of animals, data can originate from various locations such as milking parlors or grazing fields. This data can be accessed remotely through a veterinary doctor's smartphone for visualization or can be stored and analyzed on the doctor's primary computer. Upon identifying symptoms indicative of an illness, a medical team is dispatched promptly to provide treatment to the affected animal.

Each animal wears various types of battery-powered autonomous sensors including, for example, a sensor to measure body temperature and a second sensor to measure blood pressure. The devices are installed in a collar on every animal. The sensors employ a single IEEE 802.15.4 interface for low-power wireless communication. Therefore, an animal is considered an IoT node equipped with a wireless communication interface, and capable of measuring and collecting data of different types. From a remote veterinary clinic, a doctor can remotely monitor the health of the cattle, by analyzing data measured by the worn sensors and collected over a wired network. For this purpose, a gateway is situated close to the farming area and is outfitted with a dual network setup comprising an IEEE 802.15.4 communication interface and a conventional wired interface for linking with a broader global infrastructure network.

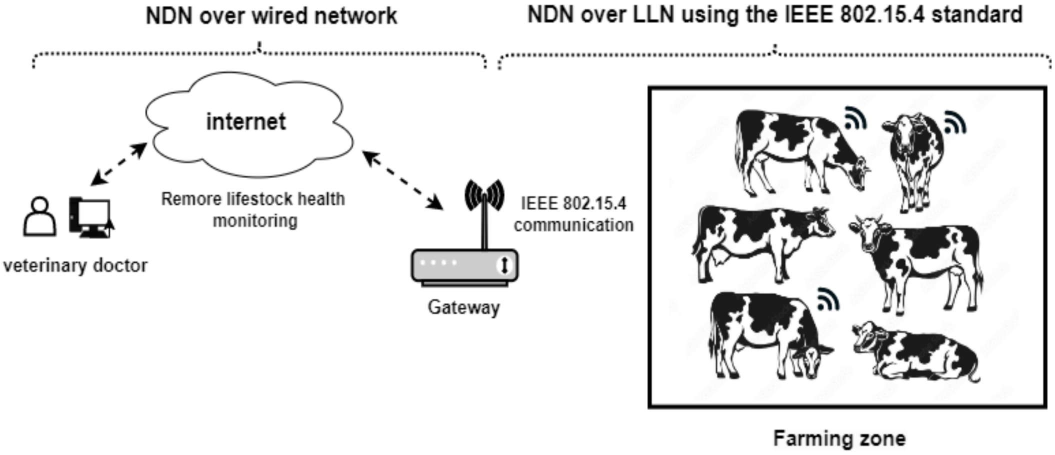


Figure 3.2: A livestock health monitoring system based on NDN over LLN using the IEEE 802.15.4 standard.

The primary objective of this system is gathering data generated by the cattle's sensors, leading to the adoption of a data-centric architecture based on the NDN framework. The NDN protocol is locally implemented on the IoT nodes within the farming area, establishing a link to the broader network via the sink node. Within the farming area, NDN nodes are mobile, and their exact locations cannot be determined in advance. Communication within this area operates on a hop-by-hop basis, facilitating packet transmission between nodes. The doctor, acting as a data consumer, regularly monitors the cattle's health status, serving as data producers, by dispatching specialized request packets to them, either collectively or targeting specific animals. In response to these requests, the respective cattle transmit data packets containing sensor readings as indicated in the requests.

The livestock health monitoring application utilizes a hierarchical and human-readable naming structure designed to be compatible with resource-constrained NDN nodes. For instance, a name can consist of three distinct fields separated by slashes ("/"), such as "/farm/animal/sensor/", where the root "farm" denotes the targeted farming area. The "animal" field serves as the unique identifier for each animal within the farming area, while the "sensor" field specifies the type of sensor being used. Consequently, when a doctor (the consumer) initiates a request containing a specific name, the corresponding animal (the producer) replies with the sensor measurement requested, encapsulated within a data packet containing both the requested name and the relevant measurement data. It is important to note that this example can be expanded to accommodate additional sensor types or even actuators as required.

3.4 NDN packets

The NDN paradigm shifts communication from location-centric to data-centric. Thus, unlike the traditional TCP/IP networks, NDN makes data the "first-class citizen" rather than "host addresses". In NDN, communication is carried out using two types of packets, namely *interest* and *data*. Consumers request content (or data) by sending interest packets in the network, prompting producers of the content to respond with corresponding data packets. This novel networking architecture incorporates inherent characteristics, including IP address-free communication and eliminating the need for establishing end-to-end connections between consumers and producers, thereby enhancing mobility support.

To provide a basic understanding of NDN, one can conceptualize it as a request-response mechanism akin to HTTP, albeit functioning at the network layer. In this analogy, a consumer represents an application generating content requests, whereas a producer denotes the application delivering responses to fulfill these requests. Unlike HTTP, which operates within the application layer of the OSI model [7], NDN diverges by utilizing packets containing names as primary information for the request-response model, with networking functionalities implemented directly within the network infrastructure.

As outlined in Figure 3.3, interest and data packets are structured to include a name field, with the possibility of additional optional fields for supplementary information. Additionally, the fields in NDN packets, including names, are encoded using the TLV (Type-Length-Value) format [77]. This format presents NDN packets as a series of TLV blocks, without a designated packet header or protocol version. Each TLV block comprises a series of bytes starting with a specific number (Type), followed by its Length and associated Value [77].

A piece of content (or data) is denoted by a URL-like hierarchical name that consists of a series of name components [78]. For instance, the name "/farm1/animal1/temp" might represent the temperature value associated with animal 1 in farm 1. By using hierarchically organized names, similar data types about other animals in another farm can be specified, such as "/farm2/animal2/temp".

Applications have the freedom to define naming schemes, allowing for flexibility in how content is named and requested. As a result, names remain opaque to the network. In practical terms, this means that intermediate relay nodes (i.e., routers) only access name components individually for routing and forwarding, without interpreting the entire name. This design choice permits application developers and users to create namespaces tailored to their requirements, eliminating the necessity to align network specifications with application configuration.

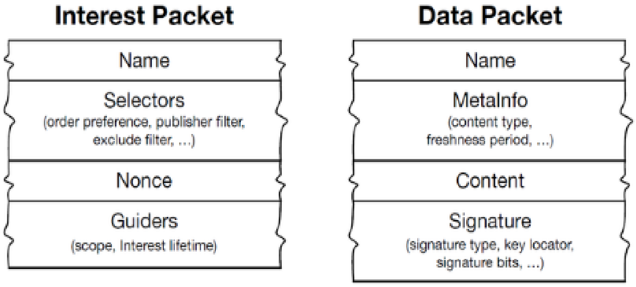


Figure 3.3: The interest and data packets used in NDN.

Applications utilize units of information, commonly known as Application Data Units (ADUs), to represent their data. For instance, in a livestock health monitoring system, ADUs could be sensor readings. In NDN-based applications, communication occurs through the exchange of interest and data packets that identify data names. When transmitting large ADUs, like video streams, over the network, one option at the application level is to use segmentation and/or sequencing. This method remains straightforward and does not introduce additional computation or extra headers in the link layer. However, the size of sensor readings for animal movements collected over time can increase rapidly. To transmit all the collected data, a producer may divide it into segments, each explicitly identified in the names. A common approach is to sequentially number these segments, such as using incremented numbers.

"/farm1/animal1/mvmnt/1", "/farm1/animal1/mvmnt/2", etc.

Employing NDN's name-matching capabilities of NDN, when a consumer application requests animal movement data using the name "/farm1/animal1/mvmnt/2," it will receive a corresponding data packet named "/farm1/animal1/mvmnt/2." Subsequently, the consumer can transmit interest packets specifying specific segment numbers to retrieve all segments of the requested data.

The primary distinction between TCP/IP and NDN in the handling of segmentation lies in their approach to ADU boundaries and segment numbering. TCP segments are not aligned with ADU boundaries, as these boundaries are only discernible post-segment reassembly at the receiving application. Conversely, NDN's data names reveal the ADU boundaries, ensuring segmentation aligns with these boundaries. However, dividing content into explicitly-named chunks is not always optimal. For instance, as each chunk is a signed data packet, segmentation can incur significant computational costs for both producers and consumers, especially when employing public key cryptography. Additionally, in networks with constrained Maximum Transmission Units (MTUs), such as IEEE 802.15.4, and considering the mandatory data signature size of at least 32 bytes (up to 255 bytes), accommodating every data packet within a single frame can be challenging even with segmentation.

The alternative is to consider packet fragmentation. In networks employing NDN, a hop-by-hop fragmentation and subsequent reassembly process is utilized when a packet exceeds the link's MTU. This necessitates relay nodes to reassemble each fragmented packet immediately, as they require complete interest and data packets for NDN operations like forwarding, matching, and caching. This fragmentation method appears to be the sole viable option for NDN, a rationale thoroughly discussed in [Afanasyev et al. 2015]. Various strategies have been proposed to address this issue. For instance, the study of [80] has proposed a lightweight fragmentation approach that adds a 3-byte header to each fragment to enable the transmission of large packets over IEEE 802.15.4 links, particularly useful in low-power wireless technologies. Another approach, as detailed in [81], involves introducing a new NDN message type to encapsulate message fragments. However, this method introduces added complexity to the NDN architecture, leading to increased memory consumption and control messages. Despite its utility, packet fragmentation often results in additional computational load, larger header sizes, and increased latency, particularly on devices with limited resources. Hence, it is advisable to minimize reliance on packet fragmentation and reassembly whenever feasible.

3.4.1 Interest packets

An interest packet contains multiple fields to facilitate data retrieval [77]. Alongside the essential "Name" field, which indicates the requested data, there is the "Nonce" field housing a four-byte random value. The fusion of these two fields—“Name” and “Nonce”—is crucial for uniquely identifying an interest packet and serves the purpose of detecting any instances of looping interest packets. Notably, the inclusion of the "Nonce" field becomes mandatory when transmitting an interest packet across network links.

Other fields in the interest packet are optional. For instance, the “Selector” field could specify the restrictions on the returned data when more than one data packet satisfies an interest packet, whereas the “Guider” fields provide more information on interest matching or forwarding. For example, the “CanBePrefix” field in an interest packet determines if the requested name can be used as a prefix to retrieve multiple data objects. When set to true, it allows fetching data objects matching the specified prefix and its extensions, optimizing data retrieval for related objects, and reducing network overhead. Conversely, the MustBeFresh field indicates that an intermediary node cannot fulfill the interest using outdated data from its local cache, as explained in the “FreshnessPeriod” field within a data packet detailed later. Additionally, the ForwardingHint feature comprises a list of name delegations, with each delegation indicating that the desired data can be acquired by forwarding the interest packet through the specified delegation route.

In NDN, the concept of "TimeToLive" (TTL) for interest packets differs from that of IP-based networks. While TTL is commonly used in IP networks to limit packet lifespan, NDN employs a distinct mechanism known as "InterestLifetime" [77]. Unlike TTL, “InterestLifetime” enables more precise control over the lifespan of interest packets. A consumer specifies the “InterestLifetime” attribute when generating an interest packet, determining the maximum duration for which the interest remains valid within intermediate nodes. If an interest is not fulfilled within its designated lifetime, intermediate nodes discard it. This approach enhances the efficiency and granularity of interest lifespan management in NDN, ensuring that interests remain valid only for the intended duration and eliminating unnecessary forwarding when they expire. It is worth mentioning that it is the application that determines the duration for the "InterestLifetime" parameter, with a default setting of 4000 milliseconds.

The "HopLimit" field denotes the maximum number of hops permissible for an interest packet in its network traversal, represented by a 1-byte unsigned integer ranging from 0 to 255. Additionally, there exists an optional "ApplicationParameters" field within the interest packet, capable of conveying supplementary data that customize the request for specific content.

3.4.2 Data packets

A data packet represents the reply transmitted by either a producer or an intermediate relay node, housing the requested content within the local CS. This packet encompasses the name, “Metainfo”, actual data, and a signature that links the data to its name. The "Metainfo" field provides details about the data, aiding in its retrieval through various means [79].

The "Name" field remains crucial and serves the same purpose as it does in the interest packet. Within the data packet, the "Content" field holds the actual data and can accommodate any sequence of bytes. Moreover, the "FreshnessPeriod" field specifies the duration (in milliseconds) for which a node storing the data in its CS should delay before marking it as "stale". Therefore, if an interest packet includes the "MustBeFresh" field, a node is restricted from returning stale data in response to this packet. This restriction effectively treats the data as non-existent in the CS. Additionally, the optional "FinalBlockId" is utilized to identify the concluding block within a sequence of fragments.

Within a data packet, a compulsory signature field is positioned at the end of the packet. The computation for generating the signature encompasses all preceding fields before the Signature field. This Signature field consists of two consecutive TLV blocks: "SignatureInfo" and "SignatureValue." The "SignatureInfo" is inclusive in the signature computation, providing a comprehensive description of the signature, the utilized signature algorithm, and any pertinent details necessary for obtaining parent certificate(s). Conversely, the "SignatureValue" is not included in the signature computation and encompasses the actual bits of the signature, along with any additional supporting signature material.

To secure data, a producer utilizes a signing key to generate a signature. This signature links the data producer, data name, and content data, ensuring the traceability and integrity of the data. Upon receiving data packets, a consumer can authenticate and validate the packet's authenticity and integrity, regardless of the origin or retrieval method of the packet. This functionality also streamlines data distribution. As consumers are indifferent to the packet's source, NDN networks can cache data packets at intermediary nodes. Consequently, when another consumer issues an interest packet requesting identical content, the cached data packet fulfills the interest request, negating the necessity to contact the producer.

3.5 NDN data structures

An NDN node contains the following data structures: the Content Store (CS), Pending Interest Table (PIT), and the Forwarding Information Base (FIB) [16, 17, 75]. These data structures are illustrated in Figure 3.4 and are described below.

The CS serves as a temporary repository for incoming data packets. Because data packets are self-contained in terms of security and not tied to specific hosts, they can be reused to fulfill other interests that seek the same content. This inherent feature provides NDN with built-in caching within the network, managed through the CS. Upon obtaining a data packet, an intermediary NDN node may keep a copy of it in the CS before forwarding it to the subsequent destination. Due to the finite capacity of the CS, strategies such as Least Recently Used (LRU) are employed for caching placement and replacement, ensuring optimal utilization of the CS resources.

The PIT retains a record for each interest forwarded until the respective data packet arrives or the entry's lifetime times out. A standard PIT record includes details such as the interest's name, the interface(s) through which it arrived, the outgoing interface(s) it was forwarded to, and a timer to manage interest timeouts. These entries in the PIT help track interests, ensuring that the corresponding data packet is directed to the appropriate consumer(s) based on precise interest-data name matching. Moreover, the PIT plays a role in filtering redundant interest requests for the same content, thereby preventing unnecessary duplication.

The FIB stores details regarding the accessibility of various contents within the network. Each FIB entry links a content-name prefix with the interface(s) through which the content is accessible. Routing protocols populate the FIB, and it is consulted whenever a node must retransmit an interest packet to search for producers, utilizing the longest prefix matching. Upon finding a match, the interest packet is directed to the relevant interface(s).

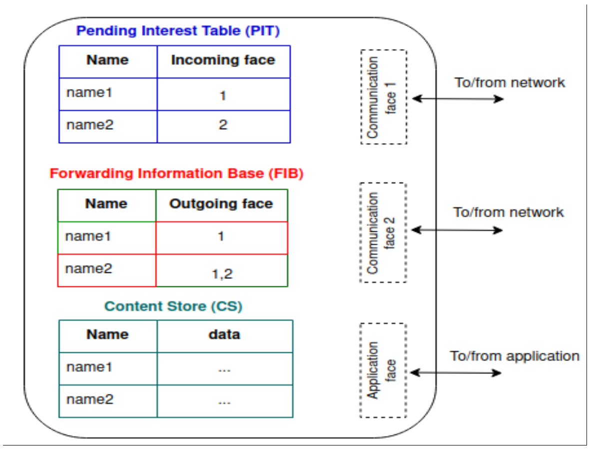


Figure 3.4: NDN nodes contain the Pending Interest Table (PIT), Forwarding Information Base (FIB), and Content Store (CS).

3.6 Interest Forwarding

NDN communication begins when a consumer initiates a data request. As shown in Figure 3.5, a consumer, i.e., a veterinary doctor in the smart livestock health monitoring application requests data by generating an interest packet carrying the name of the data, e.g. /farm1/animal1/temp. The consumer then injects the interest packet into the network through a communication interface (or face), propagating a unique name associated with the desired data. Intermediate relay nodes forward the interest packet until a data producer corresponding to the request name is located. The producer generates a data packet only in response to receiving an interest packet. The data packet follows the reverse path, initially established by the interest packet, to reach the consumer. Any intermediate node with the desired data can also respond with a data packet upon receiving the corresponding interest packet. Intermediate nodes in NDN store data packets in their CS and use them to satisfy future interest requests.

A consumer employs a proactive approach to data retrieval by issuing a new interest packet and doubling the timeout period if it does not receive a data packet within the initial timeout period [16, 17, 75]. This adaptive behavior allows a consumer to adapt to network conditions, potential delays, or data unavailability. By extending the timeout period and persisting in its data retrieval attempts, a consumer increases the chance of successfully obtaining the desired data and enhances the overall reliability of the NDN system.

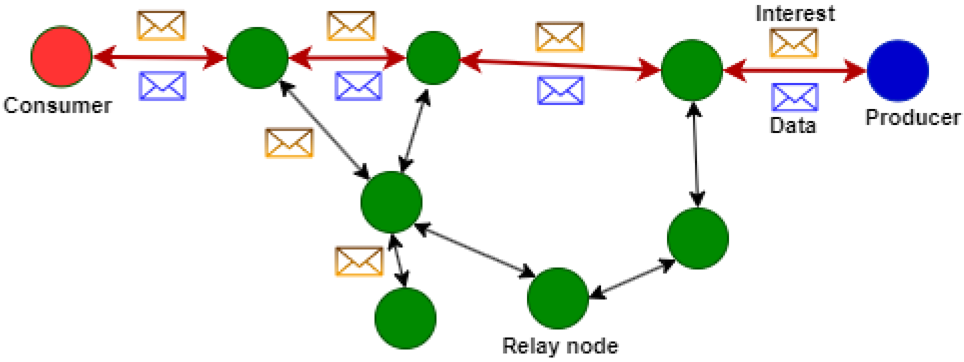
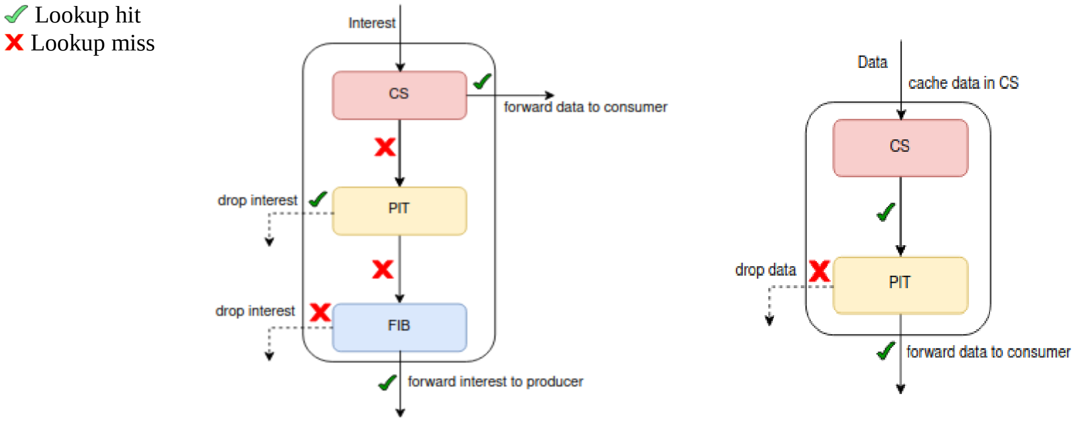


Figure 3.5: Forwarding interest and data packets between the consumer and producer in NDN.

A given NDN node utilizes the CS, PIT, and FIB to process incoming interest and data packets using the following steps. As presented in Figure 3.6, after a consumer generates an interest packet to request data, any node that receives the interest packet checks the CS to see if it already has the corresponding data. If there is a CS hit, the node sends back a data packet to the consumer without further transmitting the interest packet. However, if there is a CS miss, the node checks if the PIT has a marked entry associated with the interest packet. If there is a PIT hit, this implies that the node has already forwarded the same interest packet to search for data producers. In such a case, the node cancels the forwarding of the interest packet.

If there is no CS or PIT hit, the node creates a fresh entry in the PIT for this interest along with the associated incoming face. Subsequently, the node refers to the FIB to determine the appropriate output face for forwarding the interest packet. When the interest packet reaches a node holding the requested data (this could be the original producer), it responds by sending a data packet containing the requested content. This data packet traverses the reverse path of the interest packet, leveraging the "breadcrumb trail" established in PIT at the relay nodes. Figure 3.7 summarizes the sequence of operations carried out by a given node to forward both interest and data packets.



Processing of an interest packet

Processing of a data packet

Figure 3.6. An NDN node employs the CS, PIT, and FIB to process interest and data packets.

Both the interest and data forwarding phases in NDN rely on a broadcast mechanism using external communication faces [16, 17, 75]. During the interest forwarding phase, a consumer disseminates an interest packet to its neighboring nodes, who, in turn, replicate the process until the packet reaches a data producer. Similarly, in the data forwarding phase, a producer disseminates a data packet to all its immediate neighbors. However, only nodes with pending data requests, as indicated by the corresponding entry in the PIT, process the data packet and forward it to their neighbors. This operation is repeated until the data packet arrives at the consumer. When a receiving node does not find a matching entry in its PIT for the incoming data packet, it discards the packet after storing a copy of the data in its CS. As a result, the PIT facilitates the reverse path of data packets toward the consumers. Additionally, the PIT aids nodes to avoid potential routing loops within the network [16, 17, 75].

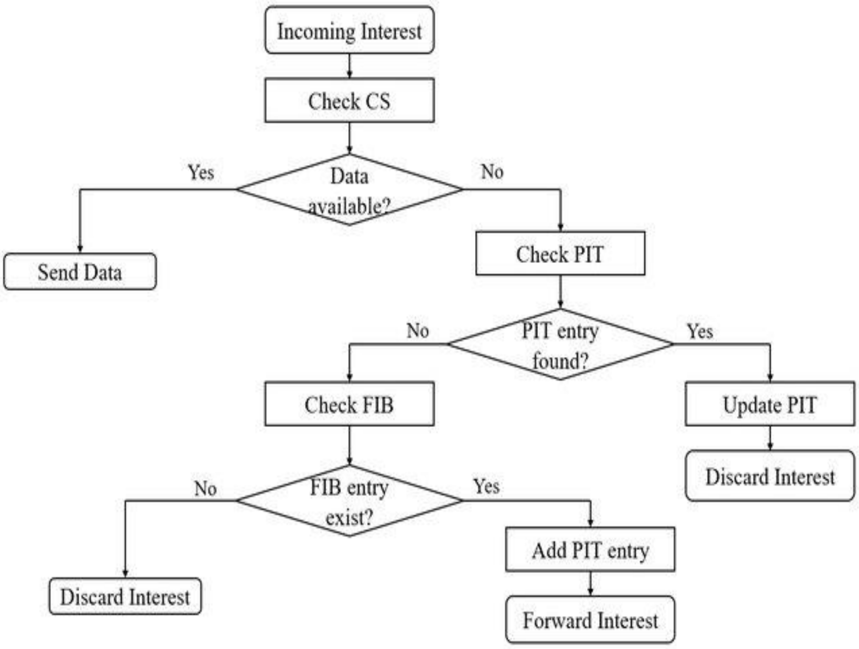


Figure 3.7: The sequence of operations carried out by an NDN node to process interest and data packets.

Example:

As illustrated in Figure 3.8, when the application in the node “Consumer 1” needs to access a piece of data in the Producer node, it generates an interest packet that contains the name of the requested data. Consumer 1 then adds a new entry in the local PIT and subsequently consults the local FIB to select a communication face to forward the interest packet to the associated data producer. The intermediate nodes rely on the PIT and FIB to advance the interest packet toward the producer location, as illustrated in Steps 1-3 in Figure 3.8. The relay nodes maintain PIT entries for outstanding forwarded interest packets, which enables interest aggregation; that is, intermediate nodes do normally not forward a second interest packet containing the same name, i.e. requesting the same data, when it has recently forwarded an interest packet for that particular data. The PIT maintains a state for all interests and maps them to network faces from where corresponding interest packets have been received. A data packet is then routed back on the reverse path using this state, as depicted in Steps 4–6 in Figure 3.8. When the data packet reaches Consumer 1, the data is passed up to the application.

Data packets received by the intermediate nodes in response to received interest packets are cached in the local CS so that subsequent interest packets from Consumer 2 requesting the same data are satisfied from that CS, as depicted in Steps 7–8 in Figure 3.8. From the perspective of a given NDN node, there is a balance of interest and data packets; that is, every single sent interest packet is satisfied by one data packet. NDN nodes can employ different strategies for interest forwarding depending on, for example, local network configuration and observed network performance. It is worth mentioning that the NDN project specifies a topology-independent naming scheme and named-based routing [75, 81].

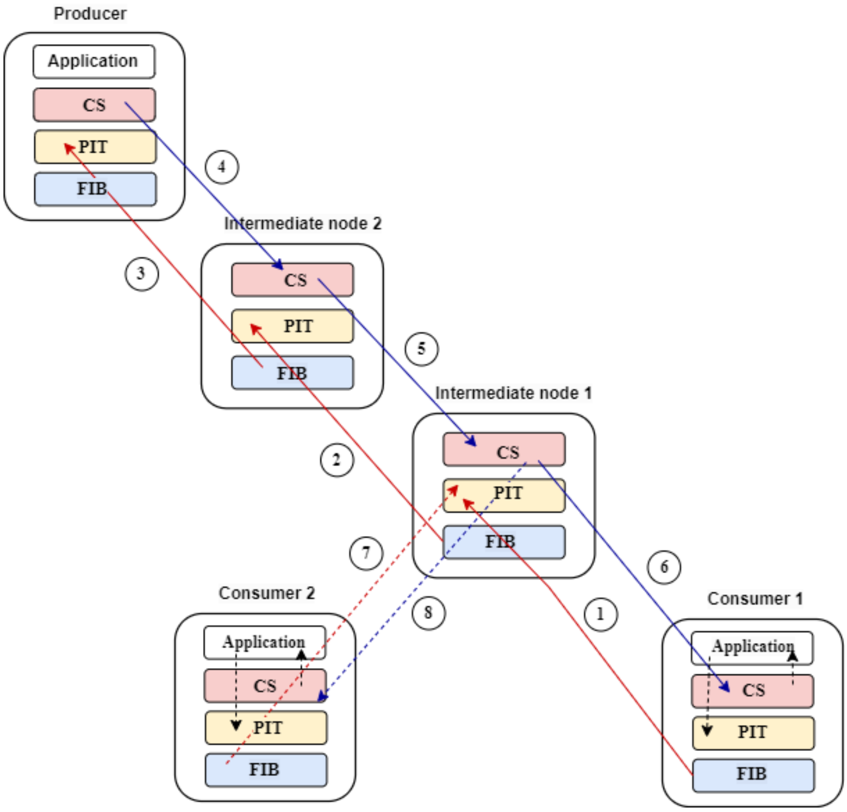


Figure 3.8: The forwarding of interest and data packets by NDN nodes.

3.7 NDN over LLNs

When NDN is deployed over wireless networks, the fundamental structure of the network nodes remains unchanged compared to the original NDN proposal, which primarily assumes a wired network environment [16, 17, 75]. Nonetheless, several unique challenges and considerations arise due to the distinct characteristics of the wireless communication medium when NDN operates over wireless networks, including LLNs. These include [30, 31, 82]:

Single communication face: Unlike wired networks, where nodes can leverage multiple communication faces for concurrent transmissions and routing, wireless nodes are constrained to a single external communication face for packet transmission. As a consequence, the handling of interest or data packets differs significantly from point-to-point communication in wired networks. In wireless setups, due to the presence of only one external communication face, packets arriving on the same face are treated differently. Unlike in wired environments where each communication link has its corresponding face, in wireless scenarios, this singular external face prohibits the separation of incoming packets based on specific links.

Additionally, the reliance on a single communication face often results in wireless nodes operating in half-duplex mode. In half-duplex mode, nodes can either transmit or receive packets at any given time but cannot perform both functions simultaneously. This mode of operation is implemented to mitigate collisions in the shared communication medium, as simultaneous transmissions from multiple nodes lead to a collision and thus packet loss. Consequently, network nodes must carefully coordinate and schedule packet transmissions to avoid packet collisions and maximize system performance. Moreover, the intermittent availability of the wireless communication channel due to half-duplex operations necessitates adaptive strategies for managing transiting traffic, handling acknowledgments, and ensuring reliable packet delivery.

Broadcast communication for data retrieval: In the realm of NDN over wireless networks, data retrieval relies on forwarding interest packets using one-hop broadcast communication of the shared wireless medium. When a node forwards an interest packet, it is received by all its neighboring nodes which are within its transmission range. This forwarding process is repeated by the neighboring nodes until a data producer is located. The limited bandwidth of a shared wireless medium can lead to congestion and bottlenecks, especially in scenarios with high data traffic or network density. This introduces challenges such as managing the broadcast storm problem, requiring efficient forwarding strategies to maintain good network performance.

Handling of Negative Acknowledgment (NACK) and duplicate packets: the operation of sending Negative Acknowledgment (NACK) packets is disabled or bypassed in NDN over wireless networks. This is due to the absence of destination addresses in both interest and data packets. This poses challenges in identifying and addressing packet loss, requiring alternative approaches to ensure reliable communication in the absence of NACK packets. Additionally, upon receiving an interest packet for the first time, a node in NDN over wireless networks stores it in the PIT. Subsequent receptions of the same interest packet are treated as loops and are therefore systematically dropped. This approach contrasts with wired point-to-point communication, where duplicate interests from the same incoming face are not considered as looping [16, 17].

Vulnerability to the broadcast storm problem: In wireless networks, nodes typically transmit packets indiscriminately in all directions due to the inherent broadcast nature of the shared wireless medium, increasing the potential risk of the broadcast storm problem [23]. This phenomenon poses a severe threat to network performance, manifesting in issues like increased channel contention, redundant packet transmissions, and frequent collisions. The consequences of a broadcast storm are detrimental degradation in network performance due to packet loss through collisions, increased network congestion, and reduced throughput. Given these challenges, it becomes imperative to devise effective solutions to mitigate the impact of the broadcast storm problem and uphold a high level of system performance. These solutions include the development of efficient interest forwarding strategies tailored to the unique characteristics of NDN over LLNs.

3.7.1 Protocol stack in NDN over LLNs

In NDN over LLNs, three layers of protocols operate within a given node, notably application, NDN, and IEEE 802.15.4 link layer, as depicted in Figure 3.9. The application layer in a consumer node generates interest packets to request data from producers, whereas the application layer in a producer node issues data packets in response to received interest packets. Interest and data packets are passed to the NDN layer through the application face. The NDN layer in a given node employs a forwarding strategy to decide whether to retransmit or drop a given interest packet through its single external face. Due to the inherent nature of the shared wireless medium, all neighboring nodes receive the interest packet. The purpose of the forwarding strategy is to mitigate the adverse impact of the broadcast storm problem and thereby guarantee the successful delivery of interest packets to producers and data packets to consumers.

The NDN layer directly interacts with the IEEE 802.15.4 link layer, facilitating the physical transfer of interest and data packets between adjacent nodes. The link layer encompasses two distinct sub-layers, namely the Medium Access Control (MAC) and Physical (PHY) sub-layers [4]. The MAC sub-layer governs access to the shared wireless medium using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm, preventing packet collisions. In contrast, the PHY sub-layer facilitates wireless communication by physically transmitting the "bits" between neighboring nodes.

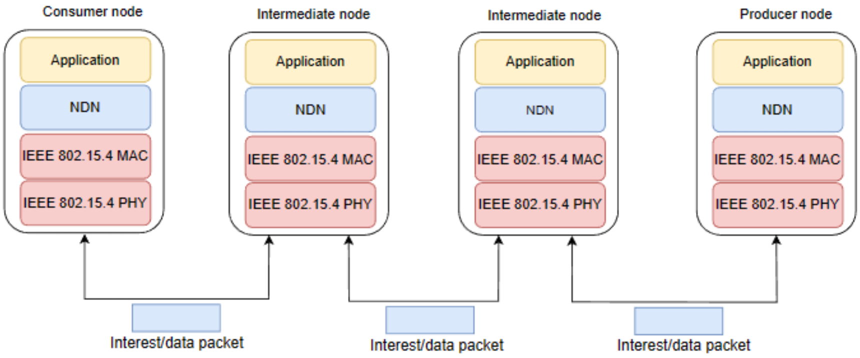


Figure 3.9: The protocol stack used by a given node in NDN over LLNs.

3.8 Summary

This chapter introduced Named Data Networking (NDN), emphasizing its foundational principles and architectural features in addressing challenges within the IoT landscape. Hierarchical naming was underscored as pivotal for efficient data representation and retrieval. Additionally, the crucial and interdependent roles of interest and data packets were discussed within NDN's data-centric framework.

This chapter has also highlighted the importance of interest forwarding in enabling seamless and efficient data delivery in NDN. Additionally, it has emphasized the challenge posed by the broadcast storm problem in NDN deployment over wireless networks, including LLNs.

The subsequent chapter will comprehensively review interest forwarding strategies that have been suggested for NDN over wireless networks, with a primary focus on LLNs. Our evaluation of the existing techniques will prioritize their suitability for this constrained environment, in terms of processing, memory, communication, and energy requirements.

4. A Review of Interest Forwarding Strategies for NDN over LLNs

4.1 Introduction

Interest forwarding in NDN is a pivotal process wherein a consumer initiates data retrieval by injecting an interest packet into the network through a communication interface (or face). This packet carries a unique name associated with the desired data. Intermediate relay nodes play a crucial role in forwarding the interest packet until a data producer corresponding to the request name is found. The producer responds with a data packet, which follows the reverse path initially established by the interest packet to reach the consumer. Any intermediate node with the desired data can also respond to the interest packet, contributing to the overall efficiency of the NDN system. This is made possible in NDN because nodes temporarily store data packets in the CS, utilizing them to satisfy future interest requests.

Both interest and data forwarding phases when NDN is deployed over wireless networks rely on one-hop broadcast communication, exploiting the inherent one-hop broadcast nature of the wireless medium, adhering to established standards such as IEEE 802.15.4 [4] or IEEE 802.11 [22]. As a consequence, a straightforward interest forwarding approach that can be easily adopted in NDN over wireless networks is Blind Flooding (BF), wherein every intermediary node broadcasts interest packets to its one-hop neighbors until a data producer is discovered. BF offers distinct advantages, characterized by simplicity, ease of implementation, and resilience, especially in scenarios involving mobility and sporadic connectivity. This is attributed to the widespread dissemination of interest packets throughout the network, ensuring comprehensive coverage to locate relevant data producers. However, the sharing of the wireless medium often results in redundant packet retransmissions, excessive channel contention, and frequent packet collisions. These issues are collectively known as the broadcast storm problem which can cause severe degradation in system performance [23].

Numerous interest forwarding strategies [24-32] have been proposed to mitigate the degrading effects of the broadcast storm problem in NDN over wireless networks. To achieve this, most existing strategies integrate one or more mechanisms to control the degree of interest forwarding in the network. These mechanisms include *forwarding*, *flooding*, *duplicate*, and *propagation* control. Forwarding control determines which network nodes are authorized to retransmit interest packets. Flooding control regulates the spatial extent to which interest packets can disseminate across all directions within the network. Duplicate control identifies and discards duplicate interest packets arriving at an intermediate node. Finally, propagation control ensures that interests advance only within specific network regions hosting potential data producers, in contrast to the broader dissemination achieved through flooding control.

Prominent examples of interest forwarding strategies for NDN over wireless networks include Deferred Blind Flooding (DBF) [30] and Learning-based Adaptive Forwarding Strategy (LAFS) [31], which employs duplicate control through listening periods. In DBF and LAFs, a relay node initiates duplicate control through a random listening period upon receiving an interest packet, discarding any duplicate interest packets received during this period. Subsequently, after the listening period concludes, the node activates forwarding control, deciding on interest retransmission based on the number of received duplicates. Retransmission is canceled if the duplicates surpass a predetermined threshold. Despite their focus on resource-constrained LLN devices and the implementation of duplicate control, LAFS and DBF encounter challenges related to excessive interest retransmissions, primarily stemming from the absence of propagation control.

Strategies such as Producer Aware Forwarding (PAF) [28] and Listen First Broadcast Later (LFBL) [34] extend DBF by introducing forwarding control as the primary step. Nodes assess eligibility for interest forwarding based on their proximity to data producers. Upon qualification, a node activates duplicate control, monitoring duplicates for a duration scaled with its distance from the producer. LFBL and PAF not only integrate duplicate control but also incorporate propagation control to constrain interest propagation to specific network regions, potentially housing data producers. This is because only nodes close to data producers can participate in the interest forwarding process. Unfortunately, the integration of propagation control can impair these strategies' ability to effectively handle producer mobility. Additionally, PAF and LFBL, designed for NDN over MANETs with IEEE 802.11 links [22], raise questions regarding their adaptability and efficacy within the context of IEEE 802.15.4-based NDN, an aspect that remains largely unexplored in the existing research literature.

This chapter provides a comprehensive review that systematically classifies the existing interest forwarding strategies explicitly designed for NDN over wireless networks. This classification is based on the specific control mechanisms employed by these strategies. A distinguishing feature of our review is its focus on lightweight strategies suitable for resource-constrained LLN devices, elucidating their primary advantages and limitations, thereby contributing valuable insights to the field.

4.2 Related work

This section comprehensively reviews the predominant forwarding strategies proposed for NDN over wireless networks. However, our central focus is on NDN over LLNs. Consequently, our evaluation of existing techniques will assess their appropriateness for this constrained environment, particularly examining their lightweight design concerning processing, memory, and communication requirements. Additionally, we will identify the specific control mechanisms employed during interest forwarding by each strategy.

To enhance the clarity of the present discussion, it is crucial to emphasize that since duplicate control is consistently succeeded by forwarding control, we uniformly refer to this combination of controls as "duplicate control". This terminology will facilitate a clear and coherent description of the different control sequences adopted by the forwarding strategies under consideration.

Direct Diffusion-NDN (dd-NDN) [12]: was primarily proposed for NDN over MANETs, operating over IEEE 802.11 links. This forwarding strategy employs randomized delay periods to mitigate packet collisions. This strategy incorporates propagation control through geo-location data to advance interest packets in the direction of data producers. More crucially, this approach diverges from the fundamental principles of NDN, as it prioritizes geo-coordinates over the actual data content. A significant drawback of this method is its reliance on geo-coordinates, particularly in three-dimensional environments, which may impose considerable memory storage requirements on individual nodes. This might be a critical issue in memory-limited LLN devices. Furthermore, the implementation necessitates an additional geo-location module, such as GPS, to determine these coordinates, making deployments in resource-constrained IoT scenarios impractical.

Geographic Interest Forwarding (GIF) [83]: was developed for NDN over MANETs. GIF involves a neighbor discovery phase employing HELLO packets and a producer discovery phase that data producers initiate to announce their presence to consumers. Moreover, nodes in GIF periodically exchange geo-coordinates to implement propagation control in that only intermediate nodes leading to producers can participate in the interest forwarding process. However, GIF may severely strain the scarce resources of LLNs due to its requirement for localization devices, such as GPS, whose energy demands might surpass the available power in inherently constrained LLNs.

Content Connectivity and Location-Aware Forwarding (CCLF) [84]: was primarily proposed for NDN over MANETs. CCLF leverages the broadcast nature of the wireless communication medium to enable nodes to make independent forwarding decisions based on per-name prefix performance measurements and available geo-location information. By incorporating a duplicate control mechanism, CCLF reduces unnecessary packet transmissions while maintaining data fetching performance comparable to flooding. However, as with GIF, the reliance on geo-location information makes this approach unsuitable for NDN over LLNs.

Location-Based Deferred Broadcast (LBDB) [85]: was designed for NDN over MANETs. In the interest flooding phase, LBDB incorporates a collision avoidance timer that reflects the forwarding priority of a node, primarily determined by the location information of the forwarding node and data producers. If during the listening period, a node overhears the same interest packet being forwarded by a neighboring node with a higher forwarding priority than itself, it cancels the retransmission of that interest. Eventually, only nodes with higher forwarding priorities forward interest packets. As a consequence, LBDB employs duplicate and propagation control to reduce interest retransmissions. However, akin to the above GIF and CCLF, LBDB encounters similar limitations due to its reliance on the geo-location information of nodes, particularly data producers.

Direction-Selective Forwarding (DSF) [86]: was proposed for large-scale NDN over Vehicular Ad hoc Networks (VANETs). In this approach, a node employs the geographical coordinates of its neighbors and additional packets (e.g., CMD and ACK) to select relay nodes based on the four quadrants of its transmission range. Consequently, DSF employs propagation control to reduce interest re-transmissions and thus saves transmission energy. In the initialization phase, consumers and producers perform random walks to create initial copies of interest and data packets inside the network. Once the initialization phase is complete, nodes forward interest packets to increase the probability of locating required data, thus reducing retrieval latency. Using geo-coordinates, coupled with the inclination towards host-centric communication rather than data-centric render DSF unsuitable for NDN over LLN deployments.

Deferred Blind Flooding (DBF) [30]: was initially devised for TCP/IP-based MANETs. Its applicability was extended to NDN over IEEE 802.15.4 links, especially when low response time is not a critical requirement [31]. DBF follows a methodology akin to Blind Flooding (BF), with an added feature to implement duplicate control. Before retransmitting an interest, a node initiates a random listening period, during which it listens to surrounding broadcasts to remove duplicate packets. At the end of the listening period, the node checks if the number of detected duplicate interest packets is above a given threshold. In this case, the retransmission of the interest packet is canceled. Otherwise, the interest packet is forwarded to the next-hop neighbors. It is worth mentioning that DBF serves as the foundational framework for other forwarding strategies, including Producer Aware Forwarding (PAF) [28], Listen First Broadcast Later (LFBL) [34], and Learning-based Adaptive Forwarding Strategies (LAFS) [31], elucidated below.

BlooGo [87]: was tailored for NDN over MANETs. BlooGo utilizes special "beacon" packets to implement duplicate control. The beacons include the ID of the sending node and a list of all their valid one-hop neighbors contained in a bloom filter field. The latter is compared with that of the receiving node, and the interest packet is forwarded to nodes not included in the incoming bloom filter. Since this solution requires beacon packets, this wastes energy and network bandwidth, which may be critical for LLN devices. Furthermore, the size of the bloom filter can exceed the maximum transfer unit (MTU) specified by the IEEE 802.15.4 standard [4], leading to frequent packet fragmentation/reassembly.

Redundancy Elimination Forwarding (REF) [87]: prioritizes the look-up of the PIT over that of the CS to reduce duplicate packet re-transmissions, and minimize search overhead associated with the CS lookup. Upon receiving an interest packet, instead of checking the CS for the associated data, the node first checks the PIT. If an entry is found in the PIT, the interest is considered a duplicate and is dropped immediately. If an entry is not found, a search in the CS is carried out. If no data is available in the CS, the interest packet is re-transmitted. The most desirable feature of REF is its ability to reduce the processing overhead of interest packets by checking the CS first and then the PIT. Nonetheless, the number of duplicate packets removed by REF is still comparable to that achieved by other forwarding strategies such as DBF [30].

Listen First Broadcast Later (LFBL) [34]: was initially suggested for MANETs within the TCP/IP framework and was recently applied to NDN over MANETs. LFBL employs both duplicate and propagation control. Each node first applies propagation control to determine whether it is an eligible forwarder based on its distance to data producers, measured by the number of hops. If a node is an eligible forwarder, it applies duplicate control where it delays interest packet retransmission for a listening period proportional to its distance to the producer. The net effect of the propagation control is that interests are propagated only in network regions closer to producers. LFBL uses a table containing estimated distances to data producers. It is worth noting that LFBL, as introduced in [34], does not employ the typical NDN data structures, namely the CS, FIB, and PIT. Instead, LFBL employs three types of packets. A Request (REQ) packet represents an interest, whereas a Responses (REP) packet represents data. A REQ packet is flooded through the network to discover available producers. An acknowledgment (ACK) packet is sent to consumers to confirm the producer. After this, relay nodes make forwarding decisions using distance tables.

Provider Aware Forwarding (PAF) [28]: is essentially LFBL augmented with the three NDN data structures, namely the PIT, FIB, and CS. In PAF, each node maintains a table that stores distance information between itself and data producers. This table is used to implement propagation control. As in LFBL, a node also employs the distance table to compute the duration of the listening period used by the duplicate control mechanism. Moreover, after receiving multiple data packets issued by potential data producers, a consumer selects the nearest among these, ensuring that the corresponding producer's ID and related distance information are carried in future interest packets. Intermediate nodes forward interest packets toward the selected producer based on the received interest packet and its local distance table.

Reinforced Learning Forwarding (RLF) [33]: was specifically tailored for NDN over LLNs. In RLF, nodes employ reinforcement learning, a subfield of machine learning, to adjust their random listening periods dynamically depending on their distance to producers during duplicate control. Initially, nodes utilize BF to flood interest packets until a producer is located. Subsequently, the producer replies by sending a data packet that includes the initial cost of zero, measured in terms of hop count. As the data packet traverses the reverse path toward the consumer, each intermediate node updates the "hopcount" cost accordingly. Nearby nodes that can overhear the transiting data packet also perform an update to learn their "hopcount" cost to the producer. Nodes constantly update their costs in the reinforcement phase. They then use the updated cost to implement propagation control since nodes with high costs are prohibited from forwarding interest packets. Furthermore, nodes use the updated cost to compute the duration of the listening period that should be applied during the duplicate control phase. The authors in [33] have shown that RLF exhibits good data delivery and low communication overhead compared to DBF [30] and DMIF [32].

Ad hoc Dynamic Unicast (ADU) [88]: is a cross-layer forwarding strategy for NDN over MANETs. ADU operates on top of the MAC layer and can dynamically switch between unicast and flooding communication modes based on notifications from the MAC layer. For this, ADU uses MAC addresses carried in data packets and stores them in the FIB, serving as the next hop for subsequent interest packets with the same name prefix. It is worth noting that ADU exploits MAC addresses to achieve propagation control. Nonetheless, this characteristic positions ADU as "conceptually" closer to the host-centric paradigm than the data-centric paradigm.

Neighborhood-Aware Interest Forwarding (NAIF) [27]: was specifically designed for NDN over MANETs. In NAIF, a node leverages broadcast overhearing within its neighborhood to gather forwarding statistics by monitoring interests and data packets forwarded by itself and its one-hop neighboring nodes. Such statistics, collected during specific update time intervals, include the following information: (i) *sint*, representing the number of distinct interest packets sent; (ii) *rdata*, indicating the number of distinct data packets received; (iii) *c*, denoting the number of distinct interest packets cleared based on the PIT; and (iv) *rint*, representing the number of distinct non-cached interest packets received. Forwarding control in NAIF relies on two locally computed parameters at each relay node: (i) the data retrieval rate, which is the ratio of successfully retrieved data packets to forwarded interest packets, and (ii) the forwarding rate, indicating the fraction of incoming interest packets that a node can forward. It is important to note that memory bandwidth is required to store rate information related to name prefixes.

Bayesian Receiver-based Forwarding Decision (BRFD) [89]: leverages the advantages of probabilistic methodologies for NDN over VANETs. The primary objective of BRFD is to mitigate the broadcast storm problem arising from interest flooding. BRFD enables vehicular nodes to make forwarding decisions autonomously based on recent insights into network conditions. Periodic sharing of status information, including driving speed, direction, and neighboring details, enables each node to calculate its forwarding probability using Bayesian decision theory. This mechanism ensures that nodes can dynamically adjust their forwarding decisions based on the prevailing network conditions. BRFD incorporates duplicate control through listening periods whose length depends on the calculated forwarding probability. This integration effectively reduces the number of duplicate interest packets, thereby enhancing data retrieval rates. BRFD requires the regular exchange of status information among neighboring nodes, which may result in high communication overhead.

Reactive Optimistic Name-based Routing (RONR) [26]: was developed for NDN over LLNs using IEEE 802.15.4 links. In RONR, interest packets are initially disseminated throughout the network using the BF strategy. Upon receiving a data packet, the consumer establishes a reverse path by following the same path initially taken by the data packet. Subsequent interest packets traverse this reverse path to reach the producer, eliminating the need for BF. Consequently, RONR exercises propagation control since interest packets advance only in the direction of the producer. Nonetheless, RONR lacks robust support for mobility or node failure, as disruptions in the path result in the scheme resorting to BF. This limitation hampers its effectiveness in maintaining efficient communication in dynamic network environments.

Dual-Mode Interest Forwarding (DMIF) [32]: was targeted for NDN over Wireless Sensor Networks (WSNs) using IEEE 80.15.4 links. In DMIF, nodes alternate between the "flooding" and "directive" modes depending on the outcome of FIB lookups on the incoming interest packets. When the FIB lookup is a hit, a relay node forwards an interest packet in the directive mode, which involves unicast communication as in RONR. When the FIB lookup is a miss, the node floods an interest packet, as in BF. Although DMIF utilizes propagation control, unicast communication may cause DMIF to suffer temporary performance degradation due to path loss caused by mobility, leading to interests dying out before reverting to flooding. As a result, DMIF may not offer efficient packet retrieval times, making it unsuitable for applications with stringent timing requirements.

Learning-based Adaptive Forwarding Strategy (LAFS) [31]: was developed explicitly for NDN over LLNs. LAFS operates in two phases. In the first phase, relay nodes apply the duplicate control mechanism of DBF. When a producer responds with a data packet, the second phase of LAFS is initiated. The data packet uses the reverse path to consumers, like in RONR. However, each relay node keeps additional information on the preceding sending node, notably the ID and distance to data producers. The node then considers the corresponding name prefix as "marked" and retransmits the subsequent interest packet with the same name prefix immediately, without going through the duplicate control mechanism. In contrast, the node subjects unmarked interest packets to duplicate control, as in DBF. While LAFS manages to reduce the number of duplicates in the network, it stores information associated with each name prefix.

4.3 Discussions

Table 1 summarizes the predominant interest forwarding strategies designed for NDN over wireless networks using IEEE 802.11 and IEEE 802.15.4 communication technologies and their essential attributes evaluated across five comparison criteria (columns). The first column, "Strategy", denotes the name of the forwarding strategy. The "Extra Packets/ Data Structures" column indicates whether a given forwarding strategy relies on additional control packets, extra fields in the interest/data packets, or data structures compared to the native NDN architecture. The "Wireless Link" column depicts the wireless communication protocol (layer 2) used by the forwarding strategy, whereas the "Control Mechanism" column denotes the control mechanisms that are incorporated within the forwarding strategy. Finally, the "Resources Requirement" column describes the functional lightness of the suggested forwarding methods, delineating their resource requirements in processing, storage, and communication.

Table 4.1: The interest forwarding strategies proposed for NDN over wireless networks with IEEE 802.11 and IEEE 802.15.4 links, listed alphabetically, and their properties are compared against four criteria (columns).

Strategy	Extra packets/ Data structures	Wireless link	Control Mechanism	Resources Requirement
ADU [88]	- Data carry MAC address - Use MAC layer notifications	IEEE 802.11	- Forwarding through the directive mode - Propagation through the directive mode	High
BF	None	IEEE 802.11 IEEE 802.15.4	- No control mechanism	Low
BlooGo [87]	- Neighbors exchange beacons - Interests carry Bloom filters	IEEE 802.11	- Forwarding through BLOOM filters	High
BRFD [89]	- Control packets to exchange status information	IEEE 802.11	- Duplicate through listening periods	High
CCLF [84]	- Uses geolocation	IEEE 802.11	- Duplicate through listening periods	High
DBF [30]	None	IEEE 802.11 IEEE 802.15.4	- Duplicate through listening periods	Low
dd-NDN [12]	- data contains the sender’s ID - next hop table	IEEE 802.15.4	- Propagation through geo-location data	High
DMIF [32]	- Keep track of name prefixes - Interests carry MAC address	IEEE 802.15.4	- Forwarding through the directive mode - Propagation through the directive mode	Medium
DSF [86]	- Uses geolocation	IEEE 802.11	- Duplicate through listening periods - Propagation through geo-coordinates	High
GIF [83]	Exchange HELLO packets	IEEE 802.15.4	- Forwarding through geo-coordinates - Propagation through geo-coordinates	High
LAFS [23]	- Data carry extra fields - Distance tables	IEEE 802.15.4	- Duplicate through listening periods	Medium
LBDB [85]	- Requires geo-location data	IEEE 802.11	- Duplicate through listening periods - Propagation through geo-location	High
LFBL [34]	- Data carry extra fields - Distance tables	IEEE 802.11	- Forwarding through distance - Propagation through distance - Duplicate through listening periods	Medium
NAIF [17]	- Keep forwarding rates - Distance tables	IEEE 802.11	- Forwarding through computed rates	Medium
PAF [28]	- Interests carry extra fields - Distance table	IEEE 802.11	- Forwarding through distance - Propagation through distance - Duplicate through listening periods	Medium
REF [87]	None	IEEE 802.11	- Duplicate through PIT	Low
RLF [33]	- Interests carry extra fields - Distance table	IEEE 802.15.4	- Propagation through distance - Duplicate through listening periods	Medium
RONR [26]	- Keep track of reverse paths - Interests carry MAC address	IEEE 802.15.4	- Forwarding through the directive mode - Propagation through the directive mode	Medium

Analyzing the data provided in Table 1, it is evident that ADU and BlooGo, originally tailored for NDN over MANETs, are not suitable for NDN over LLNs due to their substantial resource demands, which pose a considerable burden on LLN devices already constrained by limited resources. A similar argument holds for CCLF, dd-NDN, DSF, LBDB, and GIF, as their reliance on geo-location introduces resource-intensive requirements beyond the capacity of LLN devices. In contrast, the remaining strategies enumerated in Table 1 exhibit designs ranging from medium to lightweight, imposing reasonable demands on LLN resources.

Examining Table 1 also reveals that most strategies do not make use of propagation control, leading to excessive retransmissions as interests are propagated into all network regions regardless of whether they contain data producers or not. Nonetheless, strategies, like dd-NDN and DSF, typically employ propagation control based on geo-location, rendering them unsuitable for the constrained environment of NDN over LLNs due to their high energy requirement to collect location information. On the other hand, approaches like PAF and LFBL incorporate estimated distances to data producers for propagation control, and employ listening periods for duplicate control. However, as these strategies have been developed for NDN over MANETs, the suitability of their propagation control mechanism has not yet been explored within the specific context of NDN over LLNs.

Reviewing the existing research literature has revealed probabilistic broadcast has been extensively explored in TCP/IP-based wireless networks, including MANETs [35-38], WSNs [39-42], and VANETs [43-46], for various purposes, including route discovery and system-wide dissemination of critical messages. Nonetheless, the merits of probabilistic solutions for interest forwarding in NDN over LLNs have remained largely uninvestigated. Probabilistic broadcast owing to its simplicity and ease of implementation could be an attractive alternative to existing forwarding strategies as the rebroadcast probability can be adjusted to reduce the number of retransmissions, and consequently mitigate the effects of the broadcast storm problem. Moreover, it can suit the limited capabilities of LLNs as far as computation, communication, and energy are concerned.

4.4 Conclusions

This chapter has provided a comprehensive review of existing interest forwarding strategies developed for NDN over wireless networks, based on the IEEE 802.11 and IEEE 802.15.4 standards. The strategies have been systematically classified according to the control mechanisms they utilize to mitigate the broadcast storm problem. These mechanisms include forwarding, flooding, duplicate, and propagation control.

Our review has also uncovered a notable gap in employing probabilistic forwarding strategies for NDN in over LLNs. Although probabilistic solutions have demonstrated their efficacy in MANETs, WSNs, and VANETs under the TCP/IP framework, their adaptation and optimization for NDN over LLNs have not been adequately pursued. This oversight is particularly critical given the inherently lightweight and resource-efficient nature of probabilistic strategies, which align well with the constraints typical of LLNs. Additionally, the chapter has pinpointed an absence of forwarding strategies in NDN over LLNs that seamlessly integrate propagation control mechanisms, essential for minimizing redundant transmissions and enhancing energy efficiency.

To address these identified shortcomings in the current research literature, the next two chapters will introduce probabilistic interest forwarding strategies specifically designed for NDN over LLNs. These novel strategies will be subjected to a thorough performance evaluation, aimed at refining parameters governing their control mechanisms and benchmarking their effectiveness against well-established existing forwarding approaches. Through this research endeavor, we aim to contribute to the advancement of interest forwarding strategies in NDN over LLNs, enhancing network efficiency and supporting the evolving requirements of IoT applications.

5. Probabilistic Interest Forwarding for NDN over LLNs

5.1 Introduction

Numerous research studies have delved into applying probabilistic techniques for network-wide information broadcast and route discovery, particularly within traditional TCP/IP protocols [36-46]. These techniques offer appealing advantages, including balanced energy usage, minimized communication overhead, and enhanced reliability in the face of failures and network dynamism. A survey conducted by [35] has categorized existing probabilistic broadcast schemes into two main classifications: fixed and adaptive. In fixed schemes, all network nodes maintain a constant forwarding probability, while in adaptive schemes, the forwarding probability dynamically adjusts based on various system parameters such as network density, node energy levels, or the number of received packets.

While probabilistic schemes have been discussed extensively for wireless networks, including MANETs [35-38], WSNs [39-42], and VANETs [43-46], their simplicity and ease of implementation make them an attractive alternative to existing forwarding strategies. The ability to adjust the forwarding probability can effectively reduce the number of retransmissions, thereby mitigating the effects of the broadcast storm problem. Moreover, these schemes are well-suited to the limited capabilities of LLNs in terms of computation, communication, and energy. However, hardly any research has evaluated these schemes within the context of NDN over LLNs. Motivated by these observations, this chapter delves into the Probabilistic Forwarding (PF) strategy, which employs forwarding control through probabilities in NDN over LLNs. Our performance analysis will reveal that PF can significantly reduce packet retransmissions and thus conserve energy. Even with this, PF can suffer from low network reachability unless the forwarding probability is high.

Gossip-based techniques are inherently probabilistic and have been shown to improve network reachability [47]. The study of [47] has shown that setting the probability at p=0.60 allows GOSSIP to perform satisfactorily in IEEE 802.11-based MANETs with TCP/IP settings. A recent study [51] has suggested a gossip-based strategy, referred to as GOSSIP, for interest forwarding in NDN over MANETs with IEEE 80.11 links. However, there is still a need to explore the performance characteristics of GOSSIP when NDN is deployed over LLNs since the IEEE 802.15.4 [4], and IEEE 802.11 links [22] exhibit significant differences, including communication coverage, power consumption, data rate, and MAC protocol. Moreover, the GOSSIP strategy employs forwarding, duplicate, and flooding control to achieve high network reachability and thus deliver good system performance. Despite their attractive features, there has been limited research so far exploring the suitability of gossip-based techniques for interest forwarding in NDN over LLNs. To fill this gap, this chapter examines the GOSSIP strategy for interest forwarding in the context of NDN over LLNs.

The remainder of this chapter is organized as follows. Section 5.2 briefly describes the operations of probabilistic forwarding in NDN over LLNs, and then conducts a performance analysis of PF to optimize its primary parameter, notably the forwarding probability. Subsequently, Section 5.3 describes the GOSSIP forwarding strategy, and then carries out a performance analysis to determine the optimal setting of the parameters governing the control mechanisms employed by this strategy. Finally, Section 5.4 concludes this chapter.

5.2 Probabilistic Forwarding (PF)

In the PF strategy, an intermediate relay node forwards an interest packet with a fixed probability p, and refrains from forwarding with a complementary probability of $1\text{-}p$. In the present study, we assume that all nodes have the same forwarding probability. This scheme turns into the BF strategy when p=1. Algorithm 5.1 summarizes the processing of interest packets arriving at a specific node, denoted as X, in the PF strategy. The algorithm takes the following input parameters: the interest packet and the probability (p) employed in the forwarding control phase.

Interest forwarding in PF is quite straightforward. When node X receives an interest packet from its neighbor Y, X enters immediately the forwarding control phase. In this phase, X generates a random number, r ($0 \leq r \leq 1$). Subsequently, X compares r with the forwarding probability p. If $r \leq p$ is satisfied, X forwards the packet to its neighboring nodes. Otherwise, it promptly drops the interest packet.

Algorithm 5.1: Processing of interest packets in the PF strategy

```
Procedure Process_Interest {
//Inputs: Interest packet and probability (p)
//Output: Node X either forwards or drops the interest packet.

    Node X receives an interest packet from neighbor Y;
    // X enters the forwarding control phase.
    X generates a random number, r ($0 \leq r \leq 1$);
    if ($r \leq p$) then {X forwards the interest packet; else X drops the interest packet;}
} // end of Procedure.
```

Existing studies [35, 95, 96] have revealed that a probability between $p \approx 0.59$ and $p \approx 0.65$ is ideal for fixed probabilistic schemes in MANETs and WSNs with conventional IP settings. However, it is not apparent that such values are still valid for IoT environments, particularly those based on NDN over LLNs, as the operating principle of NDN is different from that of the traditional IP setting. Furthermore, the optimal forwarding probability may depend on the graph-theoretic properties of network topology factors, including node density and distance, and the transmission technologies used. We say this because most existing research studies [28, 30, 84, 85, 87] have investigated the performance of probabilistic broadcast techniques assuming IEEE 802.11 technology. In contrast, LLNs are based on IEEE 802.15.4 and thus have different characteristics in terms of communication and battery power than IEEE 802.11. More importantly, to prolong their battery lifetime, IEEE 802.15.4 devices may employ a duty cycle mechanism that allows them to sleep by completely switching off the radio transceiver for predefined periods and waking up for short time intervals to check for eventual communication. Such a mechanism undoubtedly would affect broadcast communication.

5.2.1 Performance Analysis of PF

This section evaluates the impact of the forwarding probability on the performance of PF. The insights derived from this investigation offer valuable guidance for determining optimal configurations and understanding the trade-offs associated with PF, thereby facilitating the design and implementation of probabilistic forwarding strategies in NDN over LLNs. To conduct our performance analysis, we have implemented the PF strategy in ndnSIM v2.8 [90]. The simulation model is based on the following assumptions, which are commonly adopted in similar research studies [26-32].

- Nodes form an *n*x*n* square grid topology. Neighboring nodes along the X and Y dimensions can communicate with each other. However, communication along the diagonal is not possible due to the longer diagonal distance than the distance along X/Y dimensions. It is worth noting that the performance of most existing strategies, including RLF [24], LAFS [31], and DMIF [32], have been evaluated over square grid topologies.
- In addition to the stationary nodes belonging to the square grid, consumer and producer nodes move within the square topology using the random waypoint model [91]. Consumers generate interest packets at a constant rate. The interest packets are independent of each other and have a fixed length. Furthermore, producers generate data packets upon receiving interest packets. The data packets have a fixed length.
- The NDN layer in an intermediate node uses the service provided by the IEEE 802.15.4 data link layer to physically transfer interest and data packets to the one-hop neighboring nodes. The MAC sublayer employs the unslotted CSMA/CA algorithm of the IEEE 802.15.4 standard with the default settings [4]. The PHY sublayer of the IEEE 802.15.4 introduces no transmission errors. However, packets can be lost due to packet collision, which occurs when adjacent nodes transmit packets simultaneously.
- The processing time of interest or data packets due to the protocol stack in a given node is negligible.
- No faults occur in the network, and nodes never run out of battery power.

We present performance results for varying network sizes, including configurations with 4x4, 6x6, 8x8, and 10x10 nodes. Unless stated otherwise, in our simulations, we consider a scenario with one consumer and one producer moving according to the random waypoint model at a speed of 10 m/s. The consumer generates one interest packet per second. It is important to note that the conclusions drawn from our analysis are consistent across other speeds and mobility configurations, ensuring the validity and applicability of our findings. Table 5.1 provides a summary of the main parameters and the values that have been used in our simulations. It is worth noting that such parameters have also widely been adopted in similar research work [26-32, 51].

Table 5.1: Summary of the main parameters and values used in the simulation.

Parameters	Values
MAC Protocol	IEEE 802.15.4
Transmission range (m)	50
Link bandwidth (Kbps)	250
Topology	Square grid
Interest generation rate (packets/s)	1
Number of consumers	1
Number of producers	1
CS size (number of packets)	8
PIT size (number of entries)	8
Interest size (bytes)	10
Data payload (bytes)	10
Initial energy of the battery (Joules)	20
Simulation time (s)	400

We have collected statistics for the following performance metrics, which have been widely adopted in similar evaluation studies [26-32, 51].

- ***Sent interests:*** The total number of interest packets forwarded by all network nodes during the simulation time.
- ***Sent data:*** The total number of data packets forwarded by all network nodes during the simulation time.
- ***Retrieval latency:*** the time an interest packet takes to arrive at a producer plus the time a data packet takes to arrive at a consumer. An average is computed over all interest packets generated by the consumer.
- ***Success rate:*** the number of data packets successfully received by the consumer over the number of interest packets generated in the network.
- ***Remaining energy:*** The energy that remains in a node's battery at the end of the simulation over the initial energy available at the start of the simulation. An average is computed over all the network nodes. The energy model of ns-3 [92] is used to determine this performance measure.

Figure 5.1 depicts the effects of the forwarding probability on the number of sent interest packets across the four different network sizes. The findings elucidate a notable trend. As the forwarding probability increases, there is a corresponding rise in the number of sent interest packets throughout the network sizes. This stems from the fact that as the forwarding probability rises, nodes are more likely to forward interest packets upon receipt, thereby increasing the overall dissemination of interests throughout the network. This results in a higher number of sent interest packets as more nodes participate in the forwarding process. Notably, the increase in sent interests is more pronounced in larger networks, such as the 8x8 and 10x10 configurations. The impact of the forwarding probability is amplified in larger networks due to the increased number of nodes and potential forwarding paths. Consequently, the propagation of interest packets is more extensive, leading to a steeper increase in the number of sent interest packets compared to smaller networks. Additionally, in larger networks, the likelihood of multiple nodes receiving the same interest packet and subsequently forwarding it further contributes to the accelerated growth in the number of sent interest packets.

Figure 5.2 illustrates the number of sent data packets across varying forwarding probabilities. The findings reveal a consistent increase in sent data packets with increasing forwarding probabilities across different network sizes. This trend aligns with the core principle of the NDN forwarding paradigm, where intermediate nodes forward data packets only if corresponding interest packets have traversed through them previously. With a low forwarding probability, interest packets are less likely to reach producers, resulting in incomplete coverage of the network. Consequently, when data packets attempt to follow the reverse paths established by interest packets, they traverse numerous intermediate nodes. In such cases, fewer encountered nodes possess the relevant PIT entry, leading to a higher incidence of dropped data packets. Conversely, a higher forwarding probability ensures that interest packets reach a greater number of intermediate nodes, thereby providing more nodes for data packets to utilize when returning to the consumer. This increased coverage contributes to a reduction in dropped data packets.

The results depicted in Figure 5.3 show the impact of forwarding probability on retrieval latency, measured in microseconds. The figure reveals that as the forwarding probability increases beyond 0.80, a substantial reduction in latency is observed, with further increases in p resulting in marginal improvements in latency. This consistent decrease in latency with increasing forwarding probability can be attributed to the increased likelihood of interest packets reaching the producer promptly. As the forwarding probability rises, a greater proportion of intermediate nodes decide to retransmit the transiting interest packets rather than discard them, thereby obviating the necessity for interest retransmissions by the consumer. Consequently, the overall latency decreases as more intermediate nodes actively participate in forwarding interest packets toward the producer, facilitating an expedited data retrieval process.

In Figure 5.4, illustrating the results for the success rate, we observe a direct correlation between the success rate and the forwarding probability. Notably, the interest satisfaction rate increases almost linearly with the forwarding probability and reaches a plateau of around 98% when the forwarding probability rises beyond 0.80. This improvement is primarily attributed to consumer/producer mobility, wherein interest packets often traverse shorter distances to reach the producer. Similarly, data packets encounter shorter transmission paths to reach the consumer, contributing to the heightened success rate. The shorter travel distances, facilitated by consumer and producer mobility, streamline the data retrieval process, resulting in enhanced success rates compared to static scenarios [93, 94].

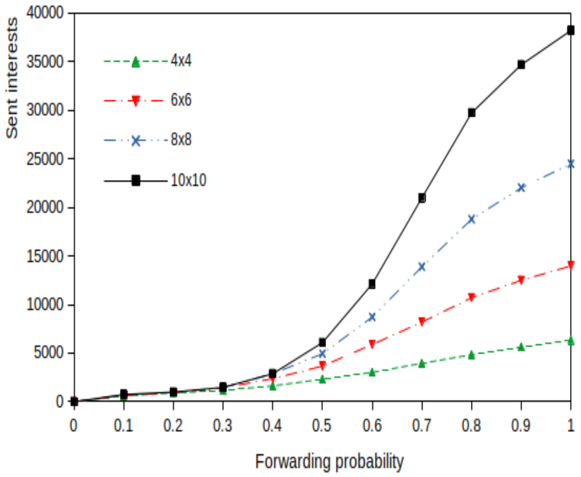


Figure 5.1: Sent interests vs. forwarding probability in PF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

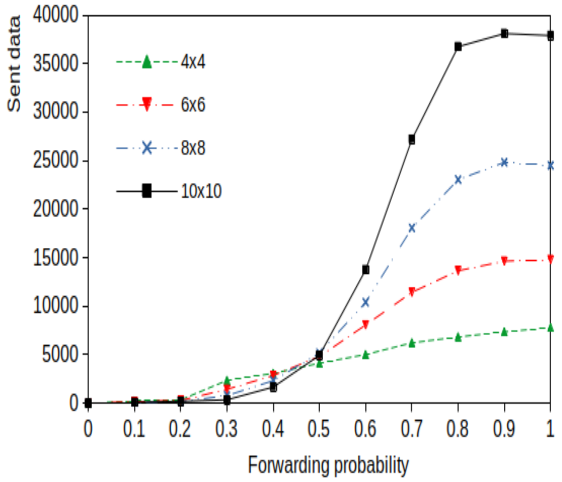


Figure 5.2: Sent data vs. vs. forwarding probability in PF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

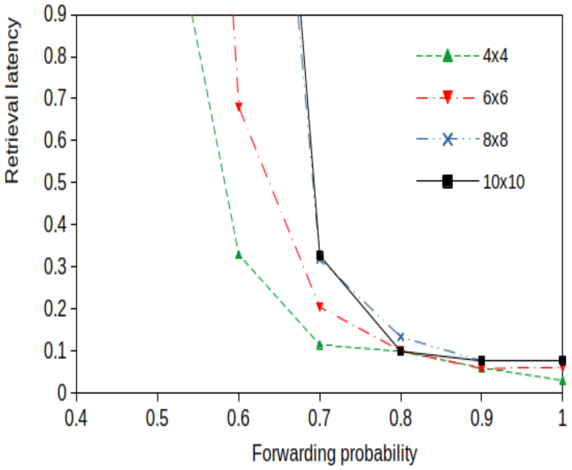


Figure 5.3: Retrieval latency vs. forwarding probability in PF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

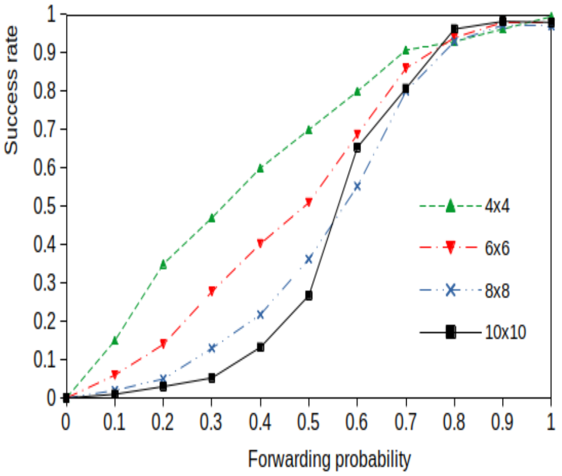


Figure 5.4: Success rate vs. forwarding probability in PF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Analyzing the relationship between remaining energy and the forwarding probability offers valuable insights into the energy efficiency of the PF strategy within the NDN framework over LLNs. As presented in Figure 5.5, a consistent trend emerges across various network sizes: an increase in the forwarding probability correlates with a noticeable decrease in remaining energy. This phenomenon arises from the heightened likelihood of relay nodes retransmitting interest packets as the forwarding probability increases, resulting in a greater number of interest packets traversing the network. Consequently, this leads to an increase in the number of sent data packets and, consequently, higher energy consumption. Conversely, lower probability values yield reduced energy consumption, resulting in higher remaining energy levels. However, this trade-off comes at the expense of reduced performance levels, as evidenced by Figures 5.3 and 5.4, which reveal higher retrieval latency and lower success rates. These findings underscore the critical importance of optimizing the forwarding probability parameter to strike a balance between efficient data delivery and energy conservation in NDN over LLNs. Such optimization holds the potential to significantly extend network lifetime and ensure sustainable operation, particularly within the resource-constrained environments typical of LLNs.

As depicted in the preceding Figures, system performance in terms of the success rate and retrieval latency improves as the forwarding probability increases. A similar performance trend for the probabilistic broadcast has been reported when applied in other contexts such as MANETs and WSNs with IP configurations [35]. However, existing studies [35, 96, 97] have found that the probability values between $p \approx 0.59$ and $p \approx 0.65$ provide the best performance results and that any further increase in the forwarding probability yields diminishing returns; i.e., little performance improvement. In contrast, we have noticed in our case that good system performance can be achieved when the probability value is $p > 0.80$, which is considerably higher than that reported in previous studies. Figure 5.4 reveals that when $p \approx 0.85$, the success rate reaches a plateau which is comparable to that achieved by higher probability values including $p = 0.90$ and $p = 1$ (i.e., blind flooding).

To justify why the forwarding probability is found to be higher in our considered scenario than in MANETs or WSNs, we should mention first that communication between adjacent nodes always occurs along the X or Y dimensions and not along the diagonal as the signal loses much of its power due to the longer distance along the diagonal. This results in the consumer and producer being separated by longer network distances compared to scenarios where communication along a diagonal direction can take place. Additionally, a higher *p* value increases the chance for packet collisions due to simultaneous packet retransmissions, in addition to the presence of hidden and exposed node problems due to the square grid topology.

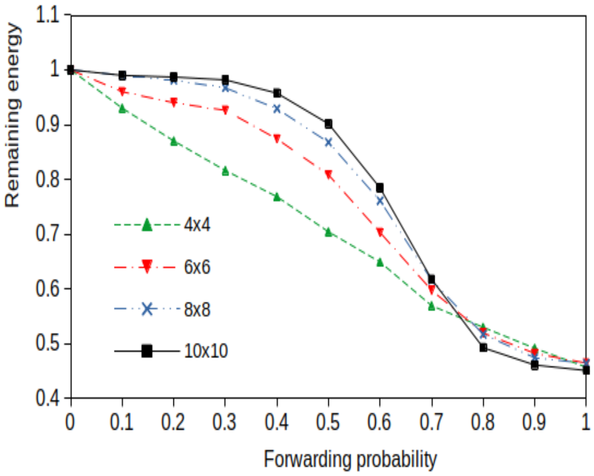


Figure 5.5: Remaining energy vs. forwarding probability in PF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

5.3 Gossip-based Forwarding (GOSSIP)

GOSSIP sequentially applies, in this order, flooding, forwarding, and duplicate control mechanisms to effectively mitigate the deleterious impact of the broadcast storm problem [51]. In GOSSIP, intermediate relay nodes initiate the flooding control phase after a consumer injects an interest packet into the network to solicit data. This phase ensures uniform dissemination of the interest packet for a fixed number of initial hops, optimizing the reach of the interest within the network. After the flooding control phase, nodes exercise forwarding control. In the forwarding control phase, relay nodes employ probabilities to introduce a randomizing element into their forwarding decisions. In cases where a node does not forward the interest packet, the node activates the duplicate control mechanism.

Algorithm 5.2 delineates the procedures for handling incoming interest packets at a designated node, referred to as X, within the framework of the GOSSIP strategy. This algorithm operates based on several input parameters, including the interest packet itself, the number of hops (*k*) employed during the flooding control phase, and the probability (*p*) applied in the forwarding control phase. Additionally, a listening period (of Δ milliseconds) is implemented during the duplicate control phase. The subsequent steps detail the actions undertaken by node X upon the reception of an interest packet from its neighboring node, Y.

- **Step 1 (Flooding control):** Upon receiving the interest packet from neighbor Y, X initiates the flooding control phase by evaluating whether the interest has traversed *k* hops. If the hop count of the interest is less than or equal to *k*, X promptly forwards the interest packet to its neighboring nodes and terminates.

- **Step 2 (Forwarding control):** If the hop count of the interest exceeds *k*, X proceeds to the forwarding control phase. Here, X generates a random number, denoted as *r*, within the range of 0 to 1. Subsequently, X compares this random number with the forwarding probability, *p*. If the condition $r \leq p$ holds, X forwards the packet to the neighboring nodes and terminates.

- **Step 4 (Duplicate control):** if $r>p$, X enters the duplicate control phase. In this phase, X initializes a duplicate counter, denoted as *c*, to one and activates a listening period lasting Δ milliseconds. During this period, X monitors incoming packets and increments the duplicate counter for each duplicate packet received. After the listening period expires, X evaluates the value of the duplicate counter. If the count is less than a specified duplicate threshold, *m*, X proceeds to forward the interest packet to its neighboring nodes. However, if the count exceeds the duplicate threshold, X discards the interest packet to reduce redundant retransmissions.

It is worth noting that when $k=0$ and $p=0$, GOSSIP reduces to DBF. In contrast, when $p=1$, the scheme reduces to BF; the parameter *m* is superfluous in this case.

Example:

In the 4x4 network displayed in Figure 5.6, the consumer and producer are situated at nodes C and P, respectively. Moreover, intermediate nodes X1 to X4, Y1, and Y2 are arranged as depicted in the diagram. For the sake of demonstration, let us suppose the number of flooding hops is set at $k=2$, the forwarding probability at $p=0.50$, and the duplicate threshold at $m=2$.

Algorithm 5.2: Processing of interest packets in the GOSSIP forwarding strategy

```
Procedure Process_Interest {
//Inputs: Interest packet, flooding hops (k), forwarding probability (p), listening period ($\Delta$), and threshold (m).
//Output: Node X either forwards or drops the interest packet.

Node X receives an interest packet from neighbor Y;
X reads the hopcount field of the interest packet;
// X enters the flooding control phase if interest's hopcount $\le k$
if (interest's hopcount $\le k$) then { X forwards the interest packet; return }

// Otherwise, X enters the forwarding control phase.
X generates a random number, r ($0 \le r \le 1$);
if ($r \le p$) then {X forwards the interest packet; return;} //X retransmits the interest to all its neighbors.

// Otherwise, X enters the duplicate control phase since X decides not to forward the interest packet.
X sets counter c= 1; X activates the listening period (for $\Delta$ milliseconds)
while ( the listening period has not expired) do {
  For (each duplicate interest packet received from neighbor Y') do {
    c=c+1; X drops the duplicate packet; }
}
// After the listening period, X checks if the number of duplicate packets is over the threshold m.
if ( c<m) then { X forwards the interest packet; else X drops the interest packet;}
}// end of Procedure.
```

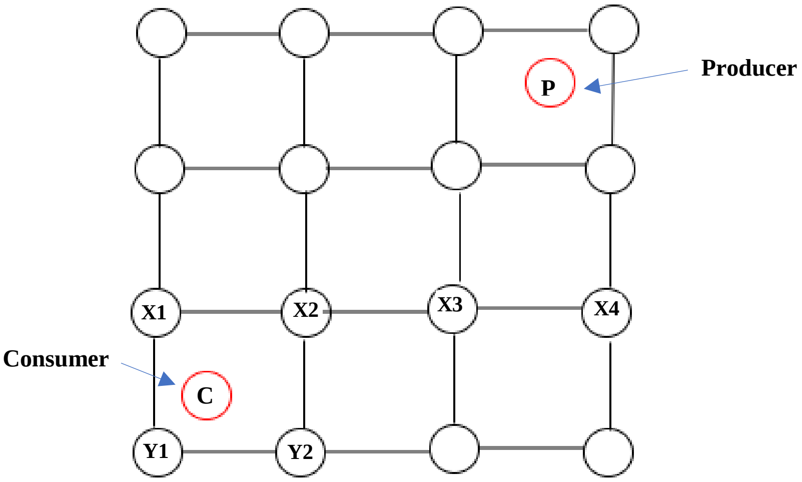


Figure 5.6: A network composed of 4 x4 stationary nodes with a consumer and producer moving within the grid. The consumer is currently located in the bottom left corner of the grid, while the producer is located at the top right corner.

Flooding Control:

Suppose that the consumer issues an interest packet, comprising the desired data name and a hopcount value of 0, to solicit data from the producer. The consumer enters the flooding control phase as the interest's hopcount is less than *k*=2. Consequently, the consumer promptly transmits the interest packet to its neighbors. For clarity, let us assume that X1 and Y1 receive the interest packet, while X2 and Y2 do not due to collisions to simplify the discussion.

Upon receiving the interest packet from the consumer, X1 increments the hopcount field in the interest packet from 0 to 1. Given that the hopcount remains below *k*=2, X1 proceeds to the flooding control phase. Thus, it promptly forwards the interest packet to its neighboring nodes, including X2. Upon receiving the interest packet, X2 increments the hopcount from 1 to 2. As the hopcount is still within k=2, X2 engages the flooding control phase and retransmits the interest packet to its neighboring nodes, including X3.

Forwarding Control:

Upon receiving the interest packet, X3 automatically increments the hopcount of the interest packet. As the hopcount surpasses k=2, X3 applies the forwarding control phase. After generating a random number, let us assume r=0.35, X3 compares it against the forwarding probability, p=0.50. Given that $r \leq p$, X3 promptly retransmits the interest packet to the neighboring nodes and concludes the process. Alternatively, if, for instance, r=0.90, surpassing p, X3 refrains from forwarding the interest and proceeds to the duplicate control phase.

Duplicate Control:

In the duplicate control phase, X3 sets the duplicate counter c=1 and initiates the listening period for Δ milliseconds. During the listening period, for each received duplicate packet, X3 increments the counter c, and drops the duplicate interest packet. After the listening period concludes, X3 compares the value of the counter against the duplicate threshold m. Suppose that c=1, implying that X has not received any duplicate packet. Since $c<m$, X3 retransmits the interest packet since it has not heard any other neighbor node retransmitting the same interest packet. Alternatively, suppose that c=2; this indicates that X3 has heard a duplicate packet. Consequently, X3 drops the packet because its neighbors have already forwarded the interest packet.

5.3.1 Performance Analysis of GOSSIP

This section conducts simulations to analyze the impact of the number of flooding hops (k), forwarding probability (p), and the duplicate threshold (m) on system performance. We aim to gain a comprehensive understanding of how these parameters influence GOSSIP's operations. The insights obtained from this analysis offer valuable guidance for determining optimal configurations and understanding the tradeoffs inherent in GOSSIP. This knowledge contributes to the development and deployment of efficient forwarding strategies for NDN over LLNs.

To carry out our study, we have implemented GOSSIP in ndnSIM v2.8 [90], using assumptions consistent with those detailed in Section 5.2. Briefly, nodes are situated in a square grid topology with one consumer sending interest packets at a constant rate of 1 packet per second. Additionally, there is one producer generating data packets upon receiving interest packets. Both the consumer and producer move within the grid following the random waypoint model at a speed of 10 m/s [91]. The listening period during the duplicate control phase follows a uniform distribution over 20 milliseconds, and unless specified otherwise, the duplicate threshold is set at m=2. Table 5.1 in our study summarizes the key parameters used in our simulations.

Performance results have been gathered using the same metrics discussed in Section 5.2. These results cover a range of network sizes, comprising setups with 4x4, 6x6, 8x8, and 10x10 nodes. Importantly, our conclusions remain consistent across different speeds and mobility setups, thereby affirming the relevance of our findings.

The number of flooding hops:

The results presented in Figure 5.7 indicate a consistent trend where an increase in flooding hops corresponds to a higher number of sent interest packets. In smaller networks, such as the 4x4 configuration, the impact of increasing flooding hops on sent interest packets shows relative stability, with minor fluctuations noted in the count of sent packets. This implies that the network size has a limited effect on the correlation between flooding hops and sent interest packets in small-scale networks. Conversely, in larger network configurations like the 10x10 nodes, a more discernable rise in sent interest packets is observed with increasing flooding hops. This can be attributed to the larger network size, which provides more opportunities for interest packets to traverse multiple hops, reaching a greater number of intermediate nodes and consequently increasing the overall count of sent packets. Additionally, as the number of flooding hops increases, since more nodes retransmit their interest packets, the likelihood of packet collision escalates. If an interest packet fails due to collisions to reach a data producer within a given timeout period, the consumer re-issues another copy of the interest packet to search for a data producer. This results in an increase in the number of sent interest packets.

The results depicted in Figure 5.8, which illustrate sent data across various network sizes, reveal a consistent decrease in sent data packets as the number of flooding hops increases. Interestingly, this decline becomes more pronounced with larger network sizes, such as the 10x10 nodes, showing a sharper decrease compared to smaller networks like the 4x4 nodes under the same flooding hop conditions. Conversely, smaller networks, such as 4x4 and 6x6 nodes, exhibit a more gradual reduction in sent data as flooding hops increase. This decrease in sent data packets with increased flooding hops can be attributed to the heightened probability of interest packet collisions during their journey through the network. This is due to the increased forwarding of interest packets by intermediate nodes, leading to a convergence of GOSSIP strategy behavior towards that of the BF strategy. Consequently, interest packets traverse a reduced number of relay nodes. Following the NDN framework, data packets trace a reverse path established by interest packets, thereby passing through a lower number of intermediate nodes. This phenomenon contributes to the observed decrease in sent data packets.

Figure 5.9 illustrates that in small networks, such as 4x4 and 6x6 nodes, there are slight variations in retrieval latency across different numbers of flooding hops, indicating a gradual latency increase with higher flooding hops. Conversely, in larger networks like the 10x10 nodes, the retrieval latency remains relatively stable when the number of flooding hops is below 3. However, beyond this threshold, there is a noticeable trend of increasing retrieval latency with the number of flooding hops. This increase in latency in larger networks is primarily attributed to the growing number of intermediate nodes forwarding interest packets as flooding hops increase, thereby elevating the chances of interest packet collisions before reaching the data producer. Consequently, consumers are compelled to inject new copies of interest packets to search for the data producer, resulting in an augmented retrieval latency. Furthermore, the heightened forwarding of interest packets by relay nodes with increasing flooding hops also escalates the probability of data packet collisions, further contributing to the observed increase in retrieval latency.

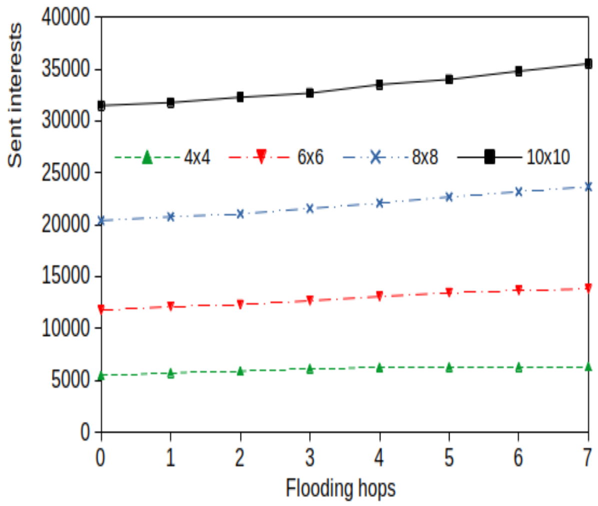


Figure 5.7: Sent interests vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

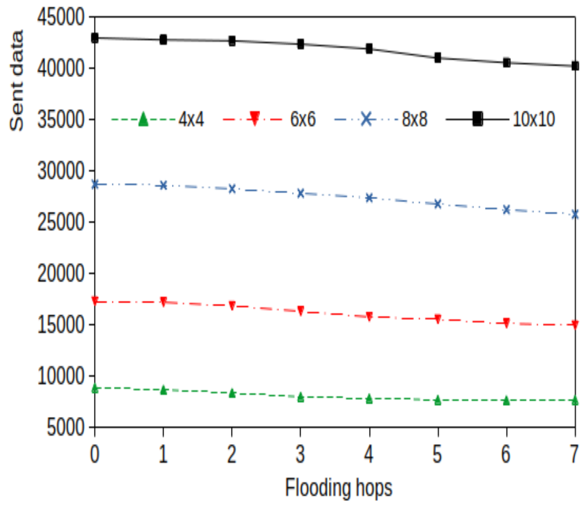


Figure 5.8: Sent data vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

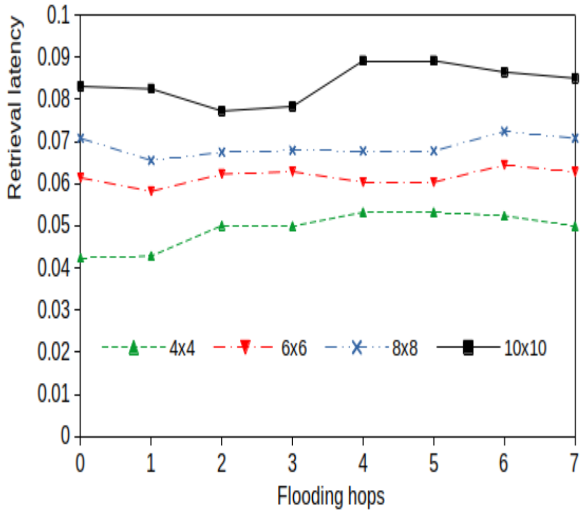


Figure 5.9: Retrieval latency vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

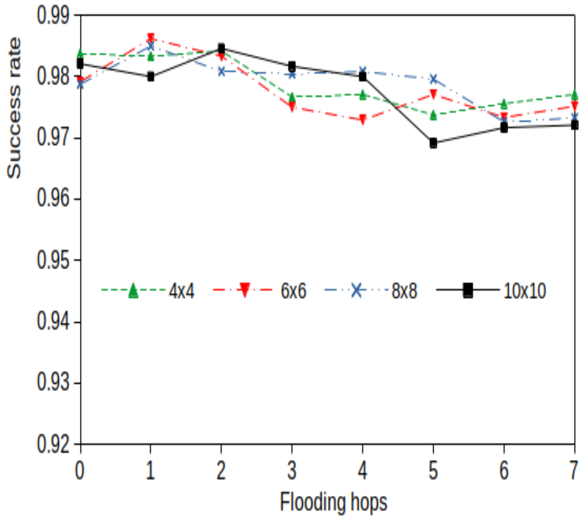


Figure 5.10: Success rate vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

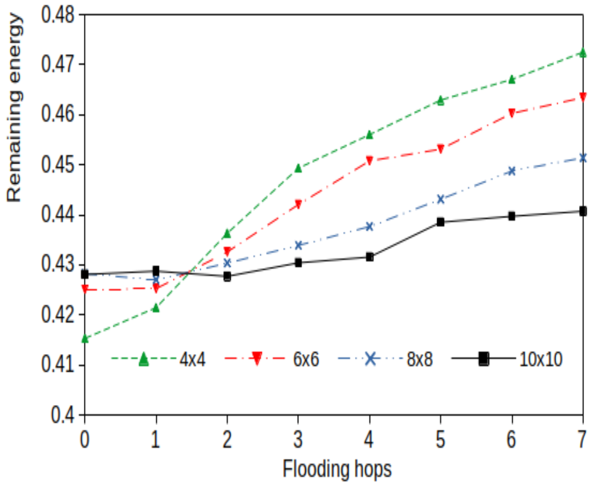


Figure 5. 11: Remaining energy vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Figure 5.10 indicates that the success rate remains relatively stable despite changes in flooding hops, with minor fluctuations observed. However, in larger networks like the 10x10 nodes, a slight decline in success rate, typically not exceeding 1.5%, is observed as the number of flooding hops increases beyond 5. This marginal decrease can be attributed to the increased chance of packet collisions with higher levels of flooding and longer path lengths in larger networks. Nonetheless, the success rate achieved by the GOSSIP strategy exhibits limited sensitivity to changes in flooding hops across all network sizes. This resilience can be attributed to several factors, particularly the presence of consumer and producer mobility within the network. The movement of consumers and producers ensures that interest and data packets can reach their destinations even in the presence of varying routing conditions caused by different numbers of flooding hops. In GOSSIP, interest packets are propagated across all network regions, thereby increasing the likelihood of locating a data producer quickly even in the presence of mobility.

Examining the remaining energy results depicted in Figure 5.11 reveals distinct trends across various network sizes and flooding hop scenarios in terms of energy conservation. In the 4x4 network, we observe a gradual increase in remaining energy from 41% at 0 flooding hops to 47% at 7 flooding hops. This upward trend persists consistently across different flooding hop scenarios, indicating a stable behavior in terms of energy consumption. Moving to the 6x6 network, we notice a similar increase in remaining energy as flooding hops increase. However, the rate of increase appears slightly lower compared to the 4x4 network, reflecting differences in energy conservation dynamics between network sizes. The 8x8 network also demonstrates a consistent rise in remaining energy with escalating flooding hops, albeit at a slower pace than the smaller networks. This observation aligns with the increased communication distances characteristic of larger networks. In contrast, the largest network size, the 10x10 nodes, exhibits a gradual increase in remaining energy as flooding hops rise. However, the magnitude of this increase is smaller compared to the smaller network sizes, indicating a more modest energy conservation effect. It is essential to note that the remaining energy levels are significantly influenced by the total volume of interest and data packets forwarded within the network. Since forwarding these packets consumes a substantial portion of a node's energy, the observed trends in remaining energy underscore the impact of packet forwarding dynamics on overall energy conservation within the network.

Forwarding probability:

Figure 5.12 illustrates how the forwarding probability affects the total number of sent interest packets across the four network sizes. The findings indicate that as the forwarding probability increases from 0 to 0.70, there is a consistent level of sent interest packets observed regardless of network size. This phenomenon is primarily linked to the elimination of duplicate interest packets by the duplicate control mechanism. During the listening period, duplicate interest packets are filtered out, thereby reducing the overall count of sent interest packets. However, beyond a forwarding probability of 0.70, there is a gradual but steady rise in the number of sent interest packets. This increase is attributed to a higher probability of intermediate nodes forwarding interest packets without triggering the duplicate control mechanism. Consequently, duplicate packets persist within the network, particularly noticeable in larger networks characterized by increased hop counts to reach the producer.

Figure 5.13 examines the total number of sent data packets as the forwarding probability varies. The results demonstrate a consistent decrease in sent data packets as the forwarding probability increases across the network sizes. This behavior can be attributed to the fundamental principle of the NDN forwarding paradigm, where intermediate nodes forward data packets only if corresponding interest packets have already visited them. With a low forwarding probability, more interest packets are subjected to duplicate control, effectively eliminating duplicates and reducing packet collisions. As a result, interest packets can traverse a higher number of intermediate nodes during their journey. Since data packets follow the reverse paths established by interest packets, they traverse many intermediate nodes, increasing the sent data packets. Nevertheless, with a high forwarding probability, a higher number of interest packets bypass duplicate control. Consequently, the likelihood of packet collisions rises, diminishing the number of interest packets that reach intermediate nodes. Consequently, data packets visit fewer intermediate nodes, reducing the total sent data packets.

Figure 5.14 delves into the relationship between retrieval latency and the forwarding probability. The figure underscores a noticeable distinction in latency performance between smaller and larger network sizes, with smaller networks demonstrating lower latency levels. This emphasizes the substantial impact of network size on latency behavior. Moreover, the analysis reveals that in smaller networks such as 4x4, 6x6, and 8x8 nodes, the retrieval latency experiences a gradual increase at a modest pace. However, in the 10x10 network, the latency remains relatively stable as long as the forwarding probability stays below 0.3. Beyond this threshold, latency experiences fluctuations, decreasing and then rising again as the probability surpasses 0.70. These findings shed light on the fact that a higher forwarding probability contributes to less efficient data packet delivery, resulting in elevated retrieval latency.

Figure 5.15 illustrates the relationship between the forwarding probability and the success rate across various network sizes. Across most network sizes, the success rate exhibits relative stability as the forwarding probability ranges from 0 to 0.70. However, beyond a forwarding probability of 0.70, there is a modest decline in the success rate. This finding underscores that a higher forwarding probability does not necessarily guarantee a higher success rate. The increase in packet collisions associated with a higher forwarding probability results in the loss of both interest and data packets, hindering the efficient delivery of interest packets to producers and data packets to consumers. These outcomes emphasize the critical role of carefully selecting the forwarding probability to strike a balance between efficient forwarding and mitigating packet loss. Ultimately, the effectiveness of interest forwarding strategies hinges on the specific network conditions and the judicious choice of the parameters utilized by the control mechanisms in the GOSSIP strategy.

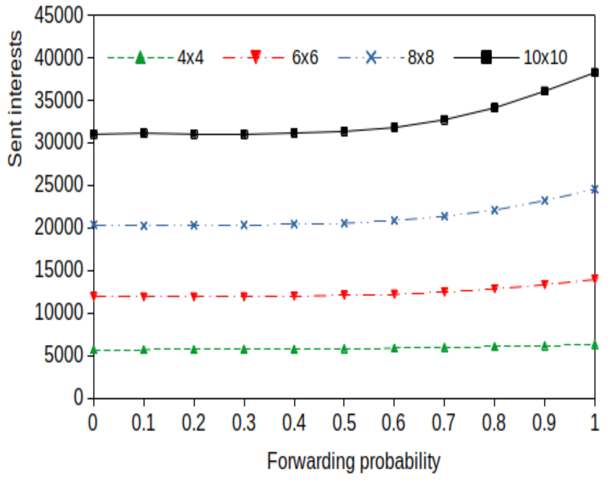


Figure 5.12: Sent interests vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

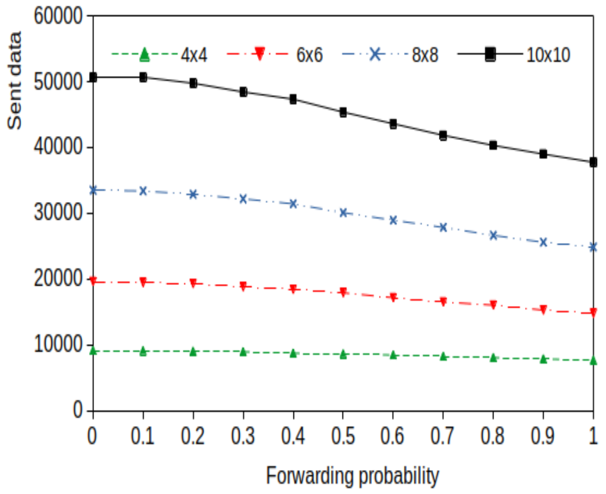


Figure 5.13: Sent data vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

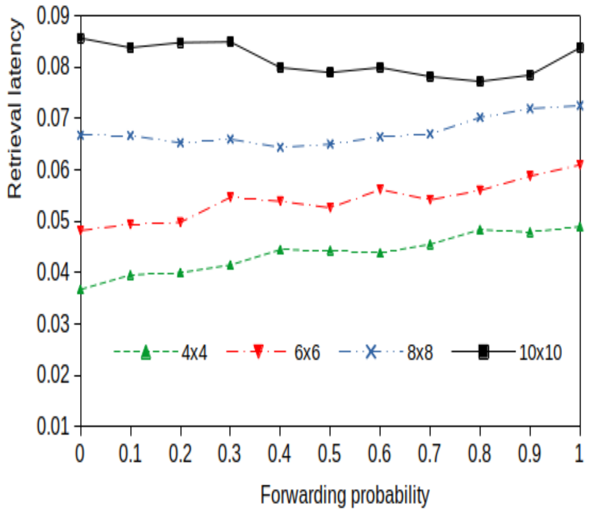


Figure 5.14: Retrieval latency vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

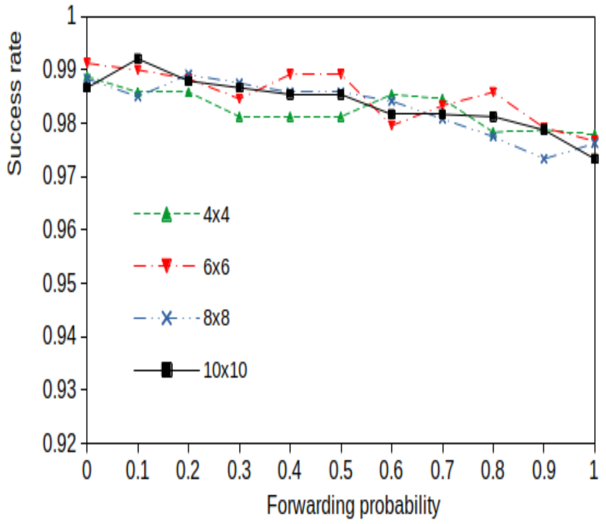


Figure 5.15: Success rate vs. number of flooding hops in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

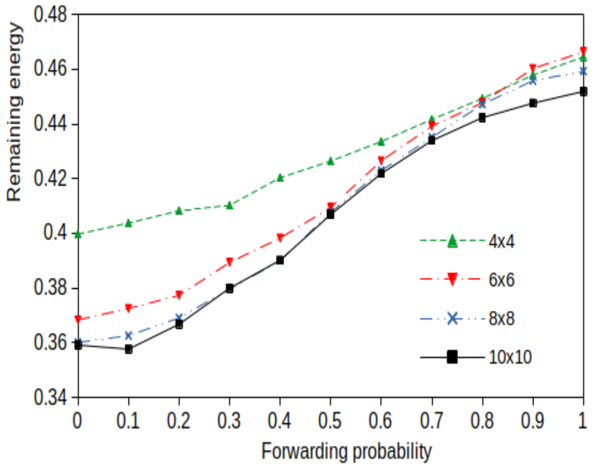


Figure 5.16: Remaining energy vs. forwarding probability in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Figure 5.16 showcases a noticeable increase in remaining energy as the forwarding probability rises. This observation is consistent across all network sizes, indicating a direct correlation between forwarding probability and energy conservation. However, it is noteworthy that in larger networks, such as the 10x10 configuration, the rate of energy increase slows down notably once the forwarding probability surpasses 0.70. This phenomenon suggests that while higher probabilities lead to improved energy conservation by minimizing unnecessary retransmissions of interest and data packets, there is a diminishing return in larger networks beyond a certain probability threshold. This trend underscores the significance of optimizing the forwarding probability parameter to strike a balance between efficient data delivery and energy conservation, especially in scenarios involving NDN over LLNs. By strategically adjusting forwarding probabilities, network architects can mitigate energy wastage, reduce packet retransmissions, and enhance overall network performance while ensuring reliable data delivery.

Duplicate threshold:

In GOSSIP, an intermediate node utilizes a threshold of received duplicate packets to determine whether to forward or discard an interest packet after the listening period concludes. Upon the expiration of the listening period, an intermediate node tallies the number of duplicate packets received. If this count surpasses a predetermined threshold (m), the node discards the interest packet; otherwise, the node proceeds to forward the packet.

Figure 5.17 illustrates the variation in the number of sent interest packets as the duplicate threshold ranges from 2 to 5 across different network sizes. The findings reveal a notable decrease in the number of sent interest packets when the threshold is set to m=2, particularly evident in the 10x10 network. This decline occurs because, with a threshold m greater than 2, most intermediate nodes fail to receive more than two duplicates, prompting them to retransmit transiting interest packets, thereby increasing the count of sent interest packets. Furthermore, Figure 5.18 demonstrates similar performance trends in the number of sent data packets across the four network sizes. However, the number of data packets increases at a slow rate as *m* varies. As the duplicate threshold increases, intermediate nodes are less likely to drop an interest packet and instead forward it, resulting in a higher number of sent interest packets visiting intermediate nodes leading to an increase in the sent data packets.

Figure 5.19 delves into the correlation between retrieval latency and the duplicate threshold across the four network sizes. The findings reveal that the retrieval latency values for *m*=2 are comparable to those for the threshold *m*=3. The observed marginal decrease in retrieval latency as the threshold increases further can be attributed to intermediate nodes forwarding interest and data packets more promptly, thus accelerating their delivery to data producers. It is important to highlight that within the GOSSIP strategy, intermediate nodes may discard interest packets, even along the shortest path to the producer, once they receive the specified number of duplicate packets as set by the duplicate threshold.

Figure 5.20 showcases the success rate as the threshold is varied. It can be noticed that the success rate remains consistently high at around 98.5%, with some slight fluctuations as the threshold increases. The consistently high success rate observed in GOSSIP can be attributed to several key factors inherent to this forwarding strategy. Firstly, GOSSIP enables interest packets to be propagated across all network regions due to the absence of a propagation control mechanism, thereby increasing the likelihood of reaching data producers efficiently. This network-wide propagation ensures that even in dynamic network conditions due to consumer/producer mobility, redundant paths are leveraged to maintain successful data retrieval. Additionally, the redundancy introduced by GOSSIP's flooding mechanism mitigates the impact of individual packet losses, contributing to a resilient and robust routing framework. Furthermore, the utilization of probabilistic forwarding mechanisms in GOSSIP allows for adaptive and dynamic forwarding decisions, optimizing the path selection process and contributing to the overall high success rate observed across varying duplicate thresholds.

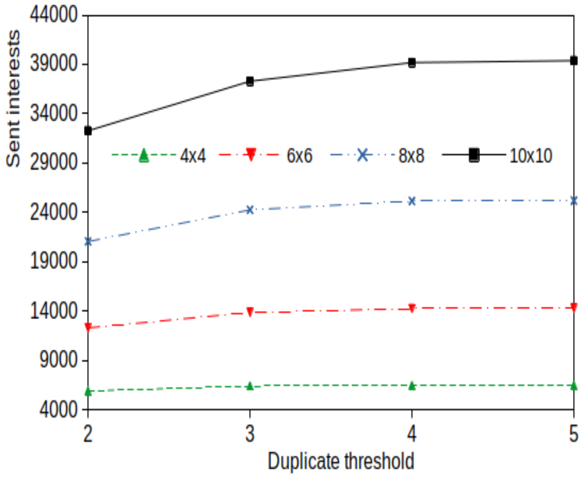


Figure 5.17: Sent interests vs. duplicate threshold in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

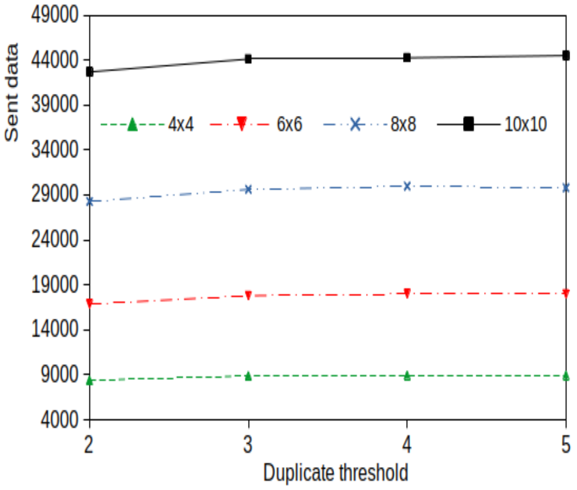


Figure 5.18: Sent data vs duplicate threshold in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

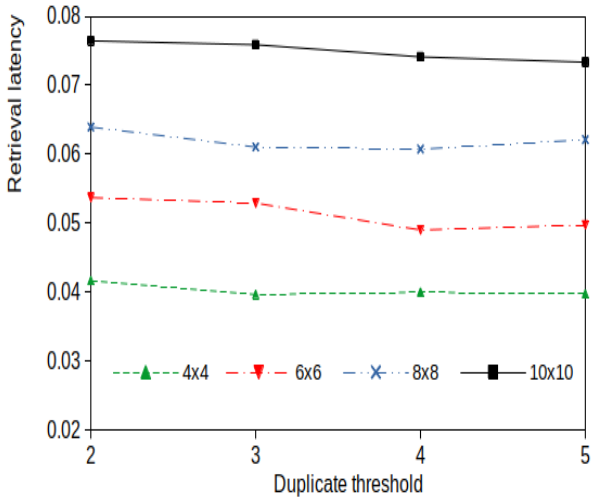


Figure 5.19: Retrieval latency vs. duplicate threshold in GOSSIP for different network sizes. The consumer generates 1 interest /s. The consumer/producer speed is 10 m/s.

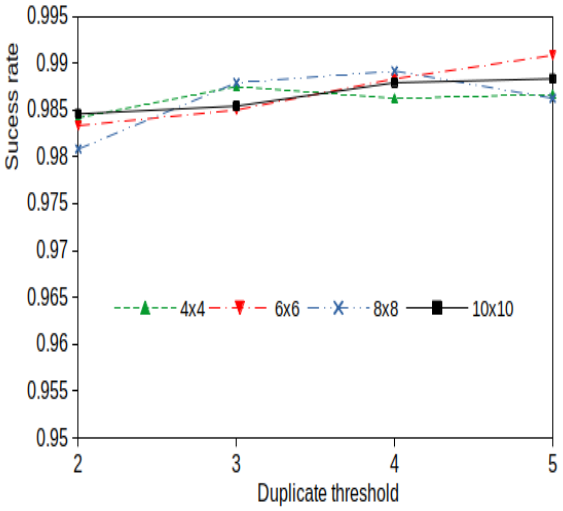


Figure 5.20: Success rate vs. duplicate threshold in GOSSIP for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

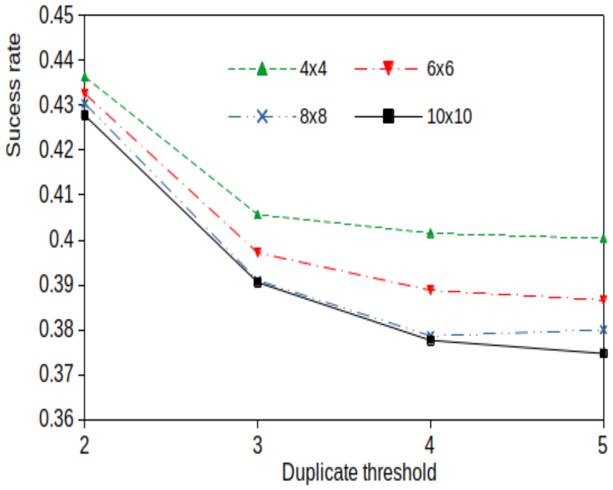


Figure 5.21: Remaining energy vs. duplicate threshold in GOSSIP for different network sizes. The consumer generates 1 interest packet/s. The consumer/producer speed is 10 m/s.

Figure 5.21 illustrates the relationship between remaining energy and threshold values for different network sizes. The graphs depict that as the threshold increases, the remaining energy steadily decreases for all network sizes. Notably, the GOSSIP strategy with a threshold of *m*=2 consistently shows lower energy consumption, and thus higher remaining energy, compared to higher threshold values for a given network size. This finding underscores the potential of GOSSIP with *m*=2 for achieving energy optimization within these networks. The lower energy consumption can be attributed to the reduced number of sent interest and data packets associated with a threshold of *m*=2, making it a promising choice for energy-efficient operations in such network environments.

In conclusion, achieving optimal performance and efficiency in real-world deployments of the GOSSIP strategy within NDN over LLNs requires a well-balanced configuration of key parameters: the number of flooding hops (*k*), forwarding probability (*p*), and duplicate threshold (*m*). Starting with the number of flooding hops (*k*), based on the performance results presented above, it is advisable to set *k* to a value of 2 or 3. This choice strikes a balance between data propagation and network efficiency, ensuring reliable data dissemination without causing excessive flooding. A lower value for *k* mitigates network congestion and reduces unnecessary packet retransmissions, thus enhancing overall network performance. Moving on to the forwarding probability (*p*), a recommended range falls between 0.6 and 0.70. This range allows for selective forwarding of interest packets while preserving energy efficiency. Such values of *p* contribute to maintaining stable packet transmission rates, facilitating efficient data delivery without overwhelming the network with superfluous traffic. Lastly, regarding the duplicate threshold (*m*), setting *m* to 2 is recommended for optimal performance. This configuration minimizes unnecessary packet transmissions and optimizes energy consumption. Notably, the analysis has demonstrated a decrease in sent interest packets when m=2, particularly advantageous in larger network sizes where efficient data delivery plays a critical role.

5.4 Conclusions

Probabilistic techniques have been extensively explored in various wireless network environments, including MANETs, WSNs, and VANETs. However, the application of such techniques within the context of NDN over LLNs has been relatively unexplored. To address this gap, this chapter has proposed the adoption of probabilistic strategies for interest forwarding in NDN over LLNs. The simplicity and ease of implementation of probabilistic solutions make them particularly suitable for NDN over LLNs, as they impose minimal additional requirements in terms of computation, communication, or storage on resource-constrained LLN devices. Moreover, they do not necessitate specific topology specifications, allowing NDN to seamlessly integrate with various routing protocols and adapt to mobile scenarios, thus helping mitigate network dynamics.

This chapter has investigated the performance properties of two probabilistic strategies, referred to as Probabilistic Forwarding (PF) and GOSSIP, in NDN over LLNs. The PF strategy, which utilizes probabilities for forwarding control, has shown promising results in reducing packet retransmissions and conserving energy. Nonetheless, our simulation results have revealed that unless the forwarding probability is set higher than 0.80, system performance, in terms of retrieval latency and success rates, can suffer due to low network reachability. In contrast, our performance analysis of the GOSSIP strategy, which employs forwarding, duplicate, and flooding control mechanisms, has demonstrated significant improvements in network reachability and overall system performance even when the forwarding probability is set low at p=0.60.

The next chapter will introduce the Distance-based Interest Forwarding (DPIF) strategy, which further optimizes probabilistic forwarding in NDN over LLNs. DPIF leverages spatial information on node proximity to data producers to exercise propagation control to enhance the effectiveness of interest forwarding in NDN over LLNs.

6. Distance-Based Probabilistic Interest Forwarding for NDN over LLNs

6.1 Introduction

Various interest forwarding strategies [24-28] have been proposed to address the challenges arising from the broadcast storm problem in NDN deployments over wireless networks using either IEEE 802.11 or IEEE 802.15.4 links. Unlike BF, which lacks a control mechanism during interest forwarding, most existing strategies integrate one or more control mechanisms to alleviate the broadcast storm problem. Such mechanisms include forwarding, flooding, duplicate, and propagation control. Forwarding control determines which network nodes are authorized to retransmit interest packets. Flooding control regulates the spatial extent to which interest packets can disseminate across all directions within the network. Duplicate control identifies and discards duplicate interest packets arriving at an intermediate node. Finally, propagation control ensures that interests advance only within specific network regions hosting potential data producers, in contrast to the broader dissemination achieved through flooding control.

In DBF [30], a relay node initiates duplicate control through a random listening period upon receiving an interest packet, discarding any duplicate interest packets received during this period. Subsequently, after the listening period concludes, the node activates forwarding control, deciding on interest retransmission based on the number of received duplicates. Retransmission is canceled if the duplicates surpass a predetermined threshold. PAF [28] extends DBF by introducing forwarding control as the primary step. Nodes assess eligibility for interest forwarding based on their proximity to data producers; distance-based forwarding in PAF inherently ensures propagation control. Upon qualification, a node activates duplicate control, monitoring duplicates for a duration scaled with its distance from the producer. After the listening period, the node reactivates forwarding control. To enhance the clarity of the present discussion, it is crucial to emphasize that since duplicate control is consistently succeeded by forwarding control, we uniformly refer to this combination of controls as "duplicate control". This terminology will facilitate a clear and coherent description of the different control sequences adopted by the forwarding strategies under consideration.

Several lightweight strategies have been devised for interest forwarding in NDN over LLNs [27, 30-33]. Prominent examples include LAFS [23] and RLF [24]. Despite their focus on resource-constrained LLN devices and the implementation of duplicate control, these strategies encounter challenges related to excessive retransmissions, primarily stemming from the absence of propagation control. In contrast, strategies, such as PAF [28] and LFBL [34], not only integrate duplicate control but also incorporate propagation control to constrain interest propagation to specific network regions, potentially housing data producers. Unfortunately, the integration of propagation control impairs these strategies' ability to effectively handle producer mobility. Additionally, PAF and LFBL, initially designed for IEEE 802.11-based NDN, raise questions regarding their adaptability and efficacy within the context of IEEE 802.15.4-based NDN. This aspect remains largely unexplored in the existing research literature.

Chapter 5 has highlighted the advantages of adopting probabilistic techniques for interest forwarding in NDN over LLNs. The main idea involves implementing forwarding control by judiciously selecting the forwarding probability, enabling the seamless integration of probabilistic solutions into resource-constrained LLN devices. In Probabilistic Forwarding (PF), a given node forwards an interest with a fixed probability, p, and refrains from forwarding with a complementary probability of $1-p$. Significantly, our investigations have revealed that contrary to recommendations for MANETs, WSNs, and VANETs with TCP/IP settings [36-46], the forwarding probability must be set noticeably high, approximately $p \approx 0.85$, to prevent interests from prematurely "dying out" before reaching data producers.

Gossip-based techniques [47] have gained widespread acceptance for broadcasting in MANETs and WSNs within the traditional TCP/IP framework [48-50]. These techniques employ forwarding, duplicate, and flooding control to achieve high network reachability even when operating with a low forwarding probability (e.g., $p \approx 0.60$) under dynamic network conditions. However, despite their proven effectiveness in minimizing interest retransmissions, both probabilistic and gossip-based methods share a common limitation—they lack a propagation control mechanism. This absence results in unnecessary interest retransmissions in network regions devoid of data producers, highlighting a crucial gap in the existing strategies that warrants further investigation and refinement. Based on these observations, this chapter introduces a novel forwarding strategy, referred to as Distance-based Probabilistic Interest Forwarding (or DPIF for short), for NDN over LLNs. DPIF optimizes interest forwarding by seamlessly integrating flooding, forwarding, propagation, and duplicate control mechanisms. A key strength of DPIF lies in its adept management of producer mobility, achieved through judicious flooding control. Additionally, DPIF leverages estimated distance to producers, probabilities, and listening periods to exercise propagation, forwarding, and duplicate control, respectively, thereby enhancing the overall efficiency of the proposed strategy. Following the description of the DPIF algorithm, a comprehensive performance analysis will be carried out to assess the impact of critical parameters governing the operations of the control mechanisms employed by DPIF on the overall system performance.

The subsequent sections of this chapter are organized as follows: Section 6.2 elucidates the operations of DPIF, providing insight into its functionalities. Section 6.3 describes the simulation model and system parameters utilized in the performance analysis. Following this, the section delves into presenting simulation results and conducting a comprehensive analysis of DPIF's performance to discern the optimal parameter configurations. Lastly, Section 6.4 offers concluding remarks for this chapter.

6.2 Distance-based Probabilistic Interest Forwarding (DPIF)

Our review of existing forwarding strategies tailored for NDN over LLNs, presented in Chapter 4, has revealed notable opportunities for enhancement. For instance, existing strategies such as DBF, LAFS, and GOSSIP incorporate a duplicate control mechanism but lack a dedicated propagation control mechanism. More crucially, while PAF integrates propagation control alongside duplicate control, it grapples with a critical drawback that can significantly impact system performance. In PAF, intermediate nodes situated farther from producers promptly discard interests, thereby not affording sufficient opportunity for interests to locate producers in dynamic mobility scenarios. These shortcomings underscore the imperative for advancements in forwarding strategies to effectively manage the interplay between mobility and interest forwarding, particularly in the context of NDN over LLNs.

To illustrate the intricacy of the issue, consider Figure 6.1, which depicts a network consisting of 16 nodes arranged in a 4x4 grid topology. The nodes are stationary, and the solid links between neighboring nodes indicate their proximity within the communication range. In addition to the stationary nodes, a consumer at node C and a producer at node P move randomly within the grid topology. Suppose the consumer is initially located in the bottom-left network region while the producer is in the top-left region, as shown in the figure. According to the operations of PAF, when the consumer generates an interest to search for the producer, nodes X1 and X2 forward the interest packet when they receive it from the consumer. In contrast, X3 and X4 drop the interest packet due to their longer distance from the producer than X1 and X2.

Suppose that, over time, the producer moves to the top-right corner. Now, X1 and X2 would drop the interest as they are further from the producer, while X3 and X4 would forward it as they become closer to the producer. However, since X3 and X4 may have dropped all the interests passing through them due to the propagation mechanism employed by PAF, they have no copies left to forward to the producer at its new location.

Existing forwarding strategies encounter challenges in effectively managing the trade-off between mobility and redundant interest retransmissions. Flooding-based strategies, like BF, DBF, and LAFS, can handle mobility but suffer from excessive retransmission redundancy, whereas distance-based strategies, like PAF, mitigate redundancy but struggle to adapt to mobility. In response to these limitations, the proposed DPIF strategy combines four key control mechanisms to optimize interest forwarding in NDN over LLNs. These include flooding control achieved through interest hopcount, propagation control through estimated distance to producers, forwarding control through probabilities, and duplicate control through a dedicated listening period. Each of these mechanisms plays a crucial role in enhancing the efficiency of interest forwarding in the context of NDN over LLNs. The purpose of each type of control is explained below.

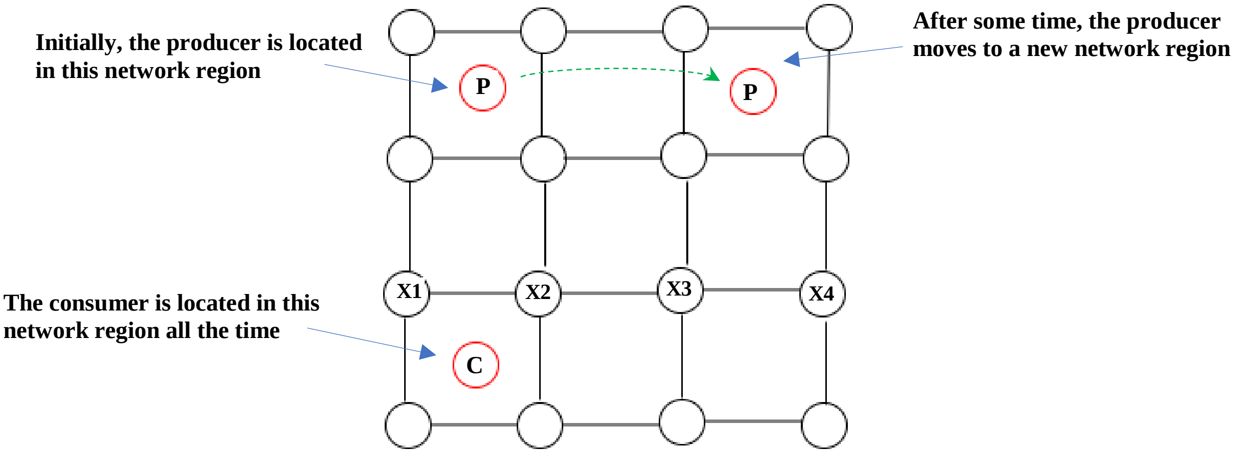


Figure 6.1: A network with 4x4 stationary nodes and a consumer and producer move within the grid. The consumer is currently at the bottom right corner of the grid, while the producer moves from the top left to the top right corner over time.

Flooding Control:

DPIF introduces a flooding control mechanism to ensure adequate dissemination of interest packets within a limited network region. When a consumer generates a new interest packet, it broadcasts the interest packet to its immediate neighboring nodes which are within its one-hop communication range. These nodes, in turn, retransmit the packet to their immediate neighbors. This flooding process is repeated for the first *k* hops made by the interest packet. This phase ensures that the interest packet is flooded in all network directions for the first *k* hops. As shown later, setting the parameter *k* to only a few hops, e.g., *k*=2, enables DPIF to exhibit favorable performance characteristics. It is worth noting that configuring *k* to match the network diameter, i.e., the longest possible distance in the network, transforms DPIF into the BF strategy.

By regulating the flooding range, which limits the number of hops an interest can advance in all network directions, the DPIF strategy balances broad coverage and adaptability to producer mobility while mitigating redundant interest retransmissions. The purpose of the flooding phase is to ensure the existence of sufficient copies of interest packets in the network, thereby facilitating the tracking of producers' movement. Additionally, this control mechanism acts as a proactive measure against the potential pitfalls of excessive network congestion, a consequence that often arises from blind flooding of interest packets. Notably, this distinctive feature sets DPIF apart from many existing strategies, which, aside from GOSSIP, generally lack a systematic mechanism to govern the extent of flooding in the network.

Propagation Control:

DPIF employs propagation control through estimated distances to producers. This control mechanism considers node proximity to a data producer to determine whether a relay node is an eligible forwarder for a given interest packet. In other words, when a node receives an interest packet from its immediate neighboring node, it compares its distance to the producer with that of the sending neighbor. If the node is closer to the producer than its neighbor, the node is an eligible forwarder of the interest packet. Otherwise, the node is not an eligible forwarder, and consequently, it promptly drops the interest packet.

Propagation control in DPIF plays a pivotal role in minimizing unnecessary interest retransmissions. Nodes strategically refrain from retransmitting interests when they do not qualify as eligible forwarders, thus contributing to a more discerning and resource-conscious approach to interest propagation. This deliberate approach results in a focused interest propagation, limiting it to network regions potentially hosting data producers. It is worth mentioning that existing strategies, except for PAF and LFBL, have sparingly used distance-based propagation control mechanisms.

Forwarding Control:

Eligible forwarders, in other words, nodes closer to producers, are preferred for efficient data retrieval. These nodes employ forwarding control through probabilities. Probabilistic forwarding introduces randomness in the decision-making process of interest forwarding. By generating a random number and comparing it to a predefined forwarding probability, nodes make informed choices regarding how to forward an interest packet. To forward an interest packet, nodes leverage the inherent broadcast nature of the shared wireless medium in LLNs to retransmit the interest packet to its immediate one-hop neighboring nodes. The broadcast operation ensures that all neighboring nodes receive the interest packet.

Probabilistic-based forwarding optimizes resource utilization by avoiding excessive interest retransmissions while maintaining sufficient dissemination. An additional pivotal advantage of probabilistic forwarding will be elaborated upon in the discussion on duplicate control. It is worth mentioning that, with the exceptions of GOSSIP and PF, existing strategies seldom integrate probabilistic forwarding into their frameworks.

Duplicate Control:

DPIF incorporates duplicate control through the judicious use of listening periods. Following a probabilistic evaluation, an intermediate node enters an active listening state if forwarding a specific interest packet is unwarranted. This listening period serves a dual purpose. First, DPIF mitigates redundant duplicate retransmissions by promptly discarding duplicate packets, thus conserving valuable network resources. Second, the listening period allows a node to re-evaluate its decision regarding interest forwarding. If the absence of duplicate packets is detected, this signals that the node might be located in an isolated network region. Consequently, the node adjusts its decision and forwards the interest packet to maintain high network reachability.

In contrast to existing strategies like DBF and PAF, where each intermediate node mandates a listening period for an interest packet at each relay node, DPIF introduces a notable optimization. Leveraging its probabilistic framework, DPIF enables interest packets to bypass the listening period at nodes where the probabilistic assessment yields a positive outcome. This strategic optimization streamlines the forwarding process and contributes to a tangible reduction in data retrieval latency.

6.2.1 The DPIF algorithm

The DPIF algorithm sequentially applies the four aforementioned control mechanisms. Intermediate nodes initiate the flooding control phase after a consumer injects an interest packet into the network to solicit data. This phase ensures uniform dissemination of the interest packet for a predetermined number of initial hops, optimizing the reach of the interest within the network. After the flooding control phase, nodes seamlessly transition to propagation control. This phase restricts the eligibility for forwarding the interest packet to nodes near data producers. In the forwarding control phase, eligible nodes employ probabilities to introduce a randomizing element into their forwarding decisions. In cases where a node does not forward the interest packet, the algorithm activates the duplicate control mechanism.

Algorithm 6.1 summarizes the processing of interest packets arriving at a specific node, denoted as X, in the DPIF strategy. The algorithm takes the following input parameters: the interest packet, the number of hops (*k*) utilized during the flooding control phase, the distance table (*D*) holding the estimated distance to data producers and the probability (*p*) employed in the propagation and forwarding control phases, respectively. The listening period (of Δ milliseconds) also serves as a parameter in the duplicate control phase. The subsequent steps elucidate the operations performed by node X upon receiving an interest packet from its neighboring node, Y.

Algorithm 6.1: Processing of interest packets in the DPIF strategy

```
Procedure Process_Interest {
//Inputs: Interest packet, number of flooding hops (k), distance table (D), probability (p), and listening period ($\Delta$).
//Output: Node X either forwards or drops the interest packet.

Node X receives an interest packet from neighbor Y;
X reads the hopcount field of the interest packet;
// X enters the flooding control phase if interest's hopcount $\le k$
if (interest's hopcount $\le k$) then { X forwards the interest packet; return }

// Otherwise, X enters the propagation control phase since the hopcount of the interest is greater than k.
X reads X_Distance from the distance table D; // X learns its distance to the producer.
X reads Y_Distance; // X learns the distance of the neighbor Y to the producer from the interest packet.
if (X_Distance>Y_Distance) then {X drops the interest packets; return;} //X is not an eligible forwarder.

Otherwise, X enters the forwarding control phase since X is an eligible forwarder.
X generates a random number, r ($0 \le r \le 1$);
if ($r \le p$) then {X forwards the interest packet; return;} //X retransmits the interest to all its one-hop neighbors.

// Otherwise, X enters the duplicate control phase since X decides not to forward the interest packet.
X sets Flag= 0; X activates the listening period (for $\Delta$ milliseconds)
while ( the listening period has not expired) do {
    For (each duplicate interest packet received from neighbor Y') do {
        X reads Y'_Distance from the duplicate interest packet;
        if ( Y'_Distance< X_Distance) then Flag=1; X drops the duplicate packet; }
}
// After the listening period, X checks if it received a duplicate packet from a neighbor closer to the producer.
 if ( Flag==1) then X drops the interest packet; else X forwards the interest packet;
} // end of Procedure.
```

- **Step 1 (Flooding control):** Upon receiving an interest packet from Y, X checks whether the interest packet has made *k* hops. If the interest's hopcount $\leq k$, X enters the flooding control phase. So, X immediately forwards the interest packet to all its immediate one-hop neighboring nodes and terminates; due to the shared wireless medium in LLNs, the forwarding operation results in the interest packet being received by all neighboring nodes that are within X's communication range.

- **Step 2 (Propagation control):** X enters the propagation control phase when the interest's hopcount$> k$. Subsequently, in this second phase, X retrieves its current estimated distance to the producer, denoted as X_Distance, by consulting its local distance table D. X also retrieves neighbor Y's distance to the producer, denoted as Y_Distance, by reading the corresponding field in the received interest packet. X then checks whether it is an eligible forwarder by comparing X_Distance with Y_Distance. If X_Distance > Y_Distance, X is farther from the producer than Y. Consequently, X is not an eligible forwarder. Thus, X drops the interest packet and terminates.

- **Step 3 (Forwarding control):** Otherwise, X enters the forwarding control phase when it is an eligible forwarder because X_Distance ≤ Y_Distance. In this phase, X generates a random number, r ($0 \leq r \leq 1$). Subsequently, X compares r with the predefined forwarding probability p. If the condition $r \leq p$ is satisfied, X appends its own X_Distance to the interest packet and forwards the packet to its immediate neighboring nodes, which are within X's communication range.

- **Step 4 (Duplicate control):** X enters the duplicate control phase when X decides not to forward the interest packet because $r> p$. X initializes the variable Flag=0 and then activates the listening period, which lasts for Δ milliseconds.

  During the listening period, for each duplicate packet received from neighbor Y', X reads the field Y'_Distance in the duplicate packet. If Y'_Distance< X_Distance, X sets Flag=1, implying that Y' is closer to the producer than X. X then drops the duplicate packet. When the listening period expires, X decides whether to forward or drop the interest depending on the flag status. If the flag is not set, this indicates that X is the closest node to the producer among its neighboring nodes. So, X appends its X_Distance to the interest packet and forwards it to its neighbors. Otherwise, X drops the interest packet since it is not on the closest path to the producer.

Example:

Consider the 4x4 network depicted in Figure 6.2, where the consumer and producer are located in nodes C and P, respectively. Furthermore, the intermediate nodes X1 to X4, Y1, and Y2 are positioned as shown in the figure. For illustration, assume that the number of flooding hops is *k*=2 and the forwarding probability is *p*=0.50. We assume that the distance tables in all nodes hold the estimated distances to the producer. Later, we will discuss a simple scheme that enables nodes to record their estimated distances to data producers.

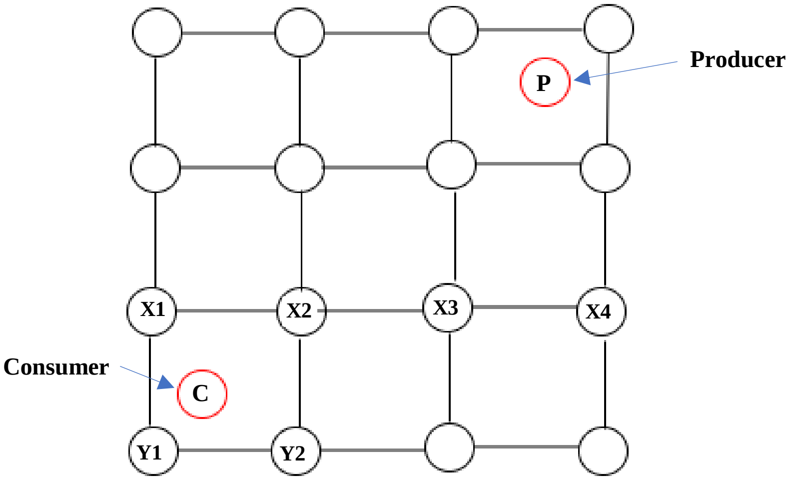


Figure 6.2: A network with 4 x4 stationary nodes and consumer and producer moving randomly within the grid. The consumer is currently located in the bottom left corner of the grid, while the producer is located at the top right corner.

Flooding Control:

Suppose that the consumer at node C generates an interest packet to request data from the producer at node P. The interest packet includes the desired data name and a hopcount value of 0. Since the hopcount is less than *k*=2, the consumer enters the flooding control phase. It consults its distance table to learn its current distance to the producer. The consumer knows it has a distance of 5, indicating that it is five hops away from the producer. The consumer inserts its distance to the producer in the associated field of the interest packet and immediately forwards the interest packet to its neighbors: X1 and Y1. To simplify the illustration, we assume that X2 and Y2 do not receive the interest packet from the consumer due to collisions.

When X1 receives the interest packet from the consumer, it automatically increments the hopcount field in the interest packet from 0 to 1. Since the hopcount is less than *k*=2, X1 enters the flooding control phase. Consequently, after retrieving its distance to the producer from its distance table, X1 includes its distance to the producer, which is 4, in the interest packet and promptly retransmits the interest packet to its immediate one-hop neighbors, including X2.

When X2 receives the interest packet from X1, it automatically increments the hopcount of the interest packet from 1 to 2. As the hopcount is 2, X2 activates the flooding control phase since the hopcount still has not exceeded *k*=2. Consequently, X2 includes its distance to the producer, which is 3, in the interest packet and forwards the interest packet to its immediate one-hop neighbors, including X3.

Propagation Control:

When the interest arrives at X3, X3 increments the hopcount of the interest packet from 2 to 3. As the hopcount is greater than *k*=2, X3 activates the propagation control phase, which immediately follows the flooding control phase. In this phase, X3 determines its forwarding eligibility. To do so, X3 consults its distance table D. X3 determines that it has a distance of 2. X3 then extracts the distance of the sending neighbor X2 from the received interest packet. X3 learns that X2's distance to the producer is 3. Because X3 is closer to the producer than X2, X3 considers itself an eligible forwarder. So, X3 enters the forwarding control phase.

Forwarding Control:

Since X3 qualifies as an eligible forwarder, it enters the forwarding control phase which follows the propagation control phase. X3 generates a random number; let us say r= 0.45. X3 then compares this random number against the forwarding probability, p=0.50. Since $r \leq p$, X3 promptly retransmits the interest packet to the immediate one-hop neighbors without activating duplicate control. For illustration, let us consider an alternative scenario in which r is greater than the forwarding probability. Let us assume that r=0.85. As $r>p$, X3 decides not to forward the interest and initiates the duplicate control phase.

Duplicate Control:

In the duplicate control phase, X3 sets Flag=0 and initiates the listening period for Δ milliseconds. During the listening period, for each received duplicate packet, X3 examines the distance of the sending neighbor Y' to the producer. If the distance of neighbor Y' to the producer is less than that of X3, X3 sets Flag=1. X3 drops the duplicate interest packet.

After the listening period expires, X3 checks the flag status. Suppose that Flag=0, indicating that X3 is the closest node among its neighbors to the producer. Therefore, X3 appends its distance to the interest packet and forwards it to its one-hop neighbors. Alternatively, suppose that X3 finds Flag=1; this indicates that X3 has heard a duplicate interest packet from a neighbor closer to the producer. Consequently, X3 drops the packet because it is not located along the shortest path to the producer relative to its neighbors. Each relay node repeats the processing of incoming interest packets according to the procedure outlined in Algorithm1 until the interest packet reaches a data producer.

6.2.2 Updating the distance to a producer

In DPIF, a node estimates its distance to producers by leveraging data packets transiting through it. As a result, upon receiving a new data packet and before starting the processing of the packet according to the NDN paradigm, node X executes the procedure, summarized in Algorithm 6.2, to update its distance table.

- **Step 1 (Initialization and update period activation):** Node X sets to "infinity" the distance to data producers in the local distance table (D). This proactive measure aids nodes in managing communication unavailability with producers, thereby preventing inaccurate forwarding decisions based on outdated information. Subsequently, X activates the update period, which lasts for ρ seconds.

- **Step 2 (Distance table update):** While the update period has not expired X repeats the following: Upon receiving a new data packet, X examines the name prefix and the hopcount field, denoting the number of hops made by the data packet from the producer to X. Node X updates the entry corresponding to the name prefix in the distance table with the fresh hopcount value, thereby recording the distance to the producer associated with the name prefix.

It is worth mentioning that other methods could be used to estimate the distance to data producers, including a weighted average as in LFBL and PAF or reinforcement techniques as in R-LF. Overall, by estimating the distance through received data packets, DPIF ensures that nodes have up-to-date knowledge of their distance to producers, improving the effectiveness of interest forwarding in NDN over LLNs.

Algorithm 6.2: Updating the distance table in the DPIF strategy

```
Procedure Update_Distance_Table {
// Inputs: Data packet, distance table (D), and update interval (ρ)
// Output: Node X updates the distance to data producers in the distance table D
X sets to "infinity" the distance to data producers in the distance table D;
X activates the update period (for ρ seconds )
While ( the update period has not expired ) do {
   X receives a data packet from neighbor Y;
   X reads the name prefix and hopcount fields in the data packet;
   X updates the entry for the name prefix with the hopcount value in the distance table D;}
} // end of Procedure.
```

6.2.3 Resource requirements of DPIF

Let us examine the computation and storage resources required by the proposed DPIF. According to Algorithms 6.1 and 6.2, the DPIF strategy has the same computational complexity as existing approaches, including DBF, GOSSIP, LAFS, and PAF. Most operations involve simple comparisons, resulting in low computational overhead. Regarding storage requirements, each node needs to maintain the distance table, D. This table consists of three fields: producer ID, distance (in hops), and time freshness (in seconds). The size of these fields varies, with the first field requiring a few bytes (e.g., 1 to 4, depending on network size), the second requiring only 1 byte (as the maximum distance is significantly lower than 256), and the third fitting comfortably within 8 bytes, depending on actual implementations. Consequently, each entry in the distance table typically occupies 16 bytes. This space requirement is comparable to existing strategies, such as PAF, LAFS, R-LF, and DMIF.

Interest packets need to include two fields: hopcount and the distance to a data producer, each requiring just one byte. Fortunately, the original NDN proposal [77] has already defined the fields "Hopcount" and "Hop Limit"; the latter can be utilized to hold the distance information. The PAF, LAFS, and R-LF strategies also employ these two fields.

To sum up, the DPIF algorithm maintains a reasonable overhead regarding computational complexity and storage requirements, aligning it with other existing strategies developed for NDN over LLNs. The simplicity of the DPIF algorithm, combined with its comparable storage demands, makes it an attractive choice for practical implementations in resource-constrained environments.

6.3 Performance Analysis of DPIF

This section analyzes the impact of critical parameters, including the number of flooding hops, forwarding probability, and the dropping criteria after the listening period expires, on the performance of DPIF. Through a thorough investigation of these parameters, we aim to gain a deeper understanding of their influence on the efficiency of DPIF. The insights derived from this investigation offer valuable guidance for determining optimal configurations and understanding the trade-offs associated with DPIF, thereby facilitating the design and implementation of interest forwarding mechanisms in NDN over LLNs

To conduct our analysis, we have implemented DPIF in ndnSIM v2.8 [90]. The simulation model is based on the same assumptions outlined in Chapter 5. We present below our performance results for varying network sizes, including configurations with 4x4, 6x6, 8x8, and 10x10 nodes. In our simulations, we consider a scenario with one consumer and one producer moving according to the random waypoint model at a speed of 10 m/s. The consumer generates one interest packet per second. It is important to note that the conclusions drawn from our analysis are consistent across other speeds and mobility configurations, ensuring the validity and applicability of our findings.

In the results reported in the figures below, unless stated otherwise, the forwarding probability in DPIF has been fixed at p=0.50. This value has been selected after a thorough analysis of the simulation results, as will be shown below. This is because it enables DPIF to exhibit the best performance tradeoffs compared to other probability settings. Table 6.1 summarizes the main parameters utilized in our simulations; such parameters and their associated values have been widely employed in similar research studies [26-32, 51].

Table 6.1: Summary of the main parameters and values used in the simulation.

Parameters	**Values**
MAC Protocol	IEEE 802.15.4
Transmission range (m)	50
Link bandwidth (Kbps)	250
Topology	Square grid
Listening period (of Δ milliseconds)	Uniformly distributed from 0 to 20
Flooding hops	2
Update period (of ρ seconds)	2
Interest generation rate (packets/s)	1
Number of consumers	1
Number of producers	1
CS size (number of packets)	8
PIT size (number of entries)	8
Interest size (bytes)	10
Data payload (bytes)	10
Initial energy of the battery (Joules)	20
Simulation time (s)	400

We have collected extensive statistics for the following performance measures: sent interests, sent data, retrieval latency, success rate, and remaining energy; the reader is kindly referred to Chapter 5 for the definition of these performance metrics.

The number of flooding hops:

DPIF exercises flooding control by regulating the number of flooding hops, denoted as *k*, in the description of the DPIF strategy outlined in Algorithm 1 above. Figure 6.3 depicts the relationship between the number of sent interest packets and the number of flooding hops. Generally, as the number of flooding hops increases, more interest packets are sent across all network sizes. This is attributed to the increased number of interest packets reaching a larger number of nodes in the network. Consequently, the number of potential forwarding nodes increases, thus increasing the overall number of sent packets. However, the rate of increase varies depending on the network size. In the 4x4 network, the number of sent interest packets remains relatively stable for different numbers of flooding hops. In contrast, larger network sizes, e.g. 8x8 and 10x10 nodes, exhibit a more significant increase in sent interests with more flooding hops. This phenomenon can be attributed to the larger number of nodes within the network, which provides more opportunities for interest packets to be forwarded and reach a larger number of intermediate nodes. Consequently, the number of sent interest packets experiences substantial growth.

Figure 6.4 reveals that the number of sent data packets exhibits comparable patterns to the number of sent interest packets reported in Figure 6.3. Increasing the number of flooding hops facilitates broader dissemination of data packets, potentially enhancing the chance of successful data delivery. However, it is crucial to consider the associated overhead and potential packet collisions that arise with an increased number of flooding hops, as they can negatively impact overall network performance and resource utilization.

Figure 6.5 shows that the retrieval latency decreases as the number of flooding hops increases from 0 to 3 across all network sizes. Beyond that, the retrieval latency remains relatively stable. For instance, in the 4x4 network, the retrieval latency values consistently remain stable as the number of flooding hops varies. In larger network sizes, such as 8x8 and 10x10, the retrieval latency exhibits a decreasing trend with an increasing number of flooding hops, ranging from approximately 0.09 to 0.07 milliseconds (ms) in the 8x8 network and from approximately 0.11 to 0.08 ms in the 10x10 network.

The results in Figure 6.6 illustrate that the success rate increases as the number of flooding hops increases across all network sizes. Higher success rates signify a greater likelihood of interest and data packets reaching the consumer and producer, respectively. In the 4x4 and 6x6 networks, the success rate is already high across all flooding hops, ranging from approximately 96% to 99%. In larger network sizes, e.g. 10x10 nodes, the success rate increases with an increasing number of flooding hops, ranging from approximately 96.5% to 98.5%.

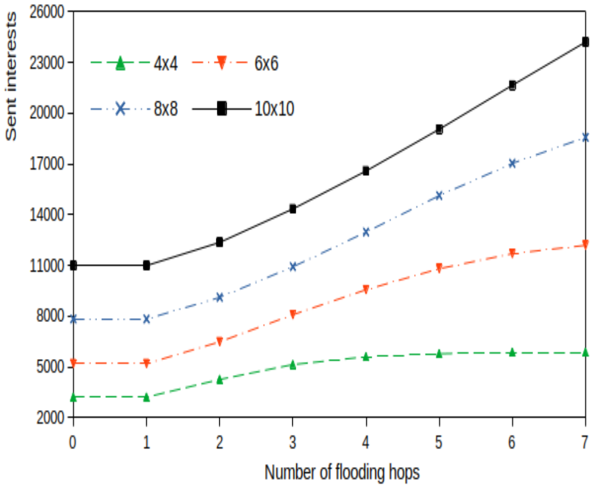


Figure 6.3: Sent interests vs. number of flooding hops in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

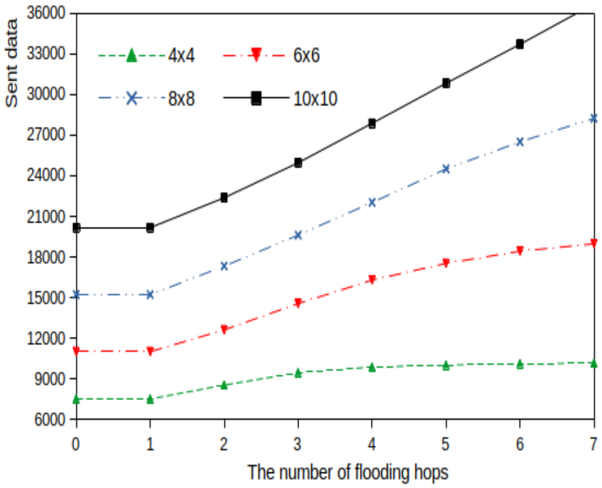


Figure 6.4: Sent data vs. number of flooding hops in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

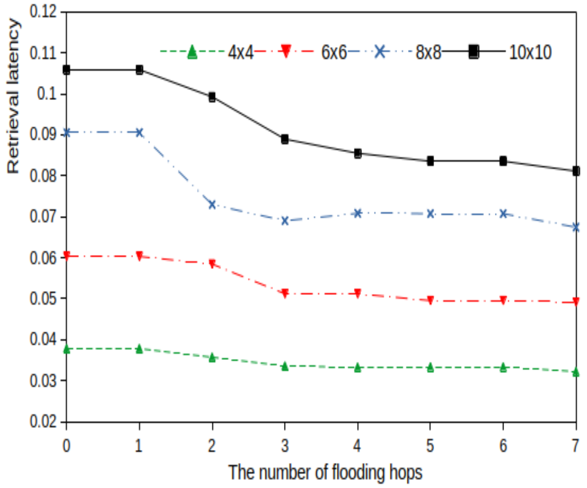


Figure 6.5: Retrieval latency vs. number of flooding hops in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

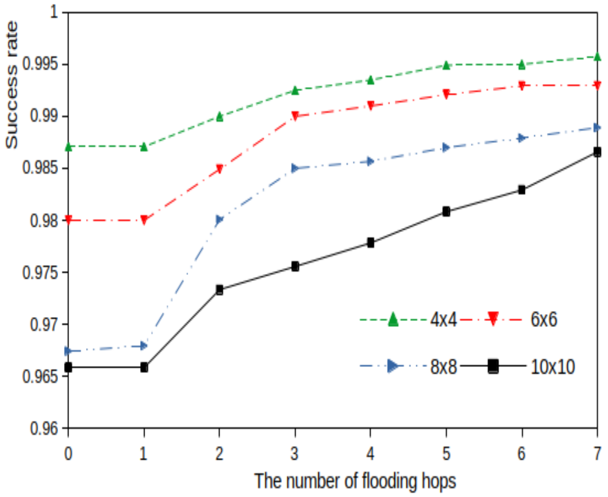


Figure 6.6: Success rate vs. number of flooding hops in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Figure 6.7 depicts the remaining energy as a function of the number of flooding hops. In general, the remaining energy decreases as the number of flooding hops increases across all network sizes. Lower remaining energy indicates higher energy consumption in the network. For example, in the 4x4 network, the remaining energy values range from approximately 50% to 35%. The decrease in remaining energy with an increasing number of flooding hops is due to the increased transmissions of interest and data packets by intermediate nodes. Similarly, in the 6x6 network, the remaining energy values range from approximately 62% to 38%. In larger network sizes, the remaining energy values decrease with an increasing number of flooding hops, ranging from approximately 72% to 44% in the 8x8 network and from 72% to 50% in the 10x10 network. These results highlight the trade-off between the number of flooding hops and energy consumption in LLN environments. While increasing the number of flooding hops may improve retrieval latency and success rate, it also leads to increased energy consumption due to the increased number of sent interest and data packets.

It is important to note that the performance results depicted in the above figures exhibit comparable trends when the parameter *k* is set to *k*=0 or *k*=1. This observation can be attributed to the fact that regardless of the parameter's value, the consumer always enters the flooding control phase, and thus floods the interest packet on its first hop upon generation. This behavior stems from the fact that when the application layer in the consumer node generates an interest packet, it automatically passes the interest down through the "application" face to the NDN layer, which immediately forwards the packet through the wireless face. When *k*=1, the consumer node still initiates the flooding control phase and thus broadcasts the generated interest on its first hop. Upon receiving the interest packet, the neighboring nodes automatically execute the flooding control phase. Consequently, these nodes flood the interest on the second hop. However, when the hopcount of the interest packet exceeds *k*, subsequent nodes cannot further flood the interest packet because the flooding control phase is completed according to the DPIF strategy. Given that the number of neighboring nodes is at most four in our analyzed grid network scenarios, similar performance behavior is obtained for *k*=0 and *k*=1.

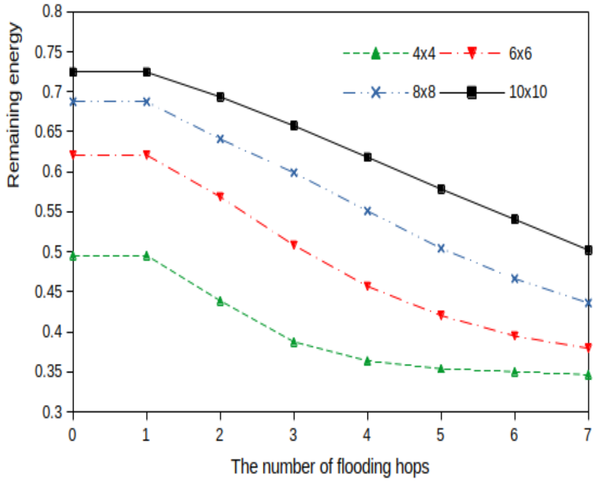


Figure 6.7: Remaining energy vs. number of flooding hops in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Our simulations have also indicated that the impact of the parameter *k* on system performance is more pronounced in larger networks, such as the 10x10 grid, than in smaller ones, such as the 4x4 grid. This is because producers can be tracked efficiently with fewer flooding hops in smaller networks. However, in larger networks, increasing *k* improves retrieval latency and success rates by generating more copies of interest packets that are disseminated across the network, expediting the location of data producers. However, this improvement comes at the expense of increased energy consumption due to additional retransmissions of interest and data packets. Notably, our performance evaluation has unveiled that setting *k*=2 enables DPIF to strike a balance between the considered metrics, delivering competitive performance characteristics across various scenarios, as will be shown below.

Forwarding probability:

Figure 6.8 illustrates the impact of the forwarding probability (p) on the total number of sent interest packets in the four network sizes. The results reveal that increasing the forwarding probability from 0 to 0.50 yields a relatively stable number of sent interest packets across the network sizes. This is attributed to removing duplicate interest packets since most interest packets go through duplicate control. During the listening period, duplicate interest packets are removed from the network, reducing the number of sent interest packets. However, beyond a forwarding probability of 0.50, the number of sent interest packets steadily increases, albeit slowly, due to a higher likelihood of intermediate nodes forwarding interest packets without activating the duplicate control mechanism. This leads to the retention of duplicate packets within the network, particularly noticeable in larger network sizes with more hops to reach the producer.

In Figure 6.9, the total number of sent data packets is examined as the forwarding probability varies. The results demonstrate a consistent decrease in sent data packets as the forwarding probability increases across the network sizes. This behavior can be attributed to the fundamental principle of the NDN forwarding paradigm, where intermediate nodes forward data packets only if corresponding interest packets have already visited them. With a low forwarding probability, more interest packets are subjected to duplicate control, effectively eliminating duplicates and reducing packet collisions. As a result, interest packets can traverse a higher number of intermediate nodes during their journey. Since data packets follow the reverse paths established by interest packets, they traverse many intermediate nodes, increasing the sent data packets. Nevertheless, with a high forwarding probability, a higher number of interest packets bypass duplicate control. Consequently, the likelihood of packet collisions rises, diminishing the number of interest packets that reach intermediate nodes. Consequently, data packets visit fewer intermediate nodes, reducing the total sent data packets.

Figure 6.10 focuses on the retrieval latency as a function of the forwarding probability. The figure shows that smaller network sizes exhibit lower latency than their larger counterparts, highlighting the impact of network size on latency performance. Furthermore, the retrieval latency remains relatively constant when the forwarding probability is below 0.5 in a given network size. However, at a forwarding probability of $p=0.50$ and higher, the retrieval latency decreases and rises again as the probability exceeds 0.70. These findings indicate that a higher probability of forwarding interest packets leads to less efficient data packet delivery, consequently leading to higher retrieval latency.

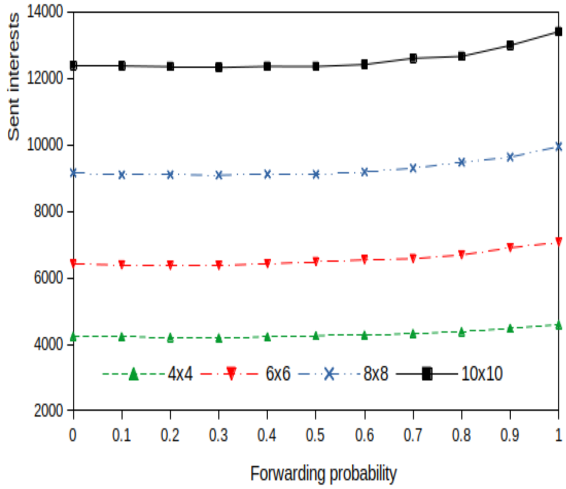


Figure 6.8: Sent interests vs. forwarding probability in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

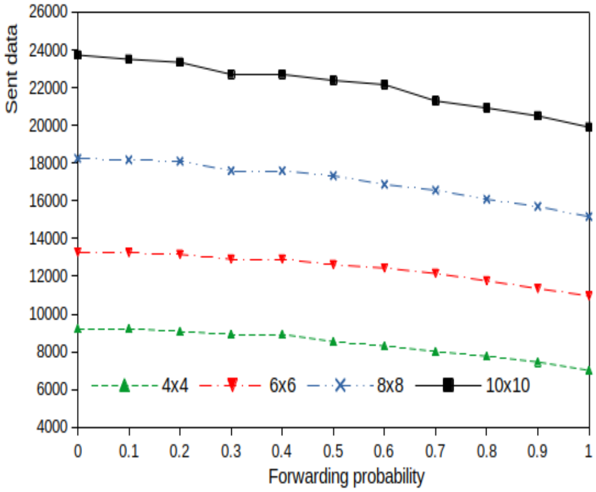


Figure 6.9: Sent data vs. forwarding probability in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

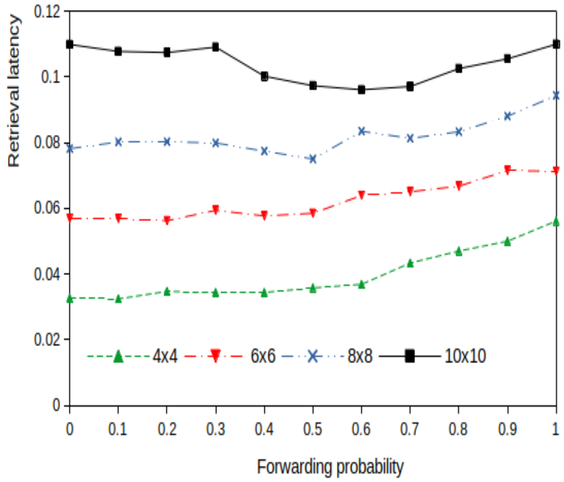


Figure 6.10: Retrieval latency vs. forwarding probability in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

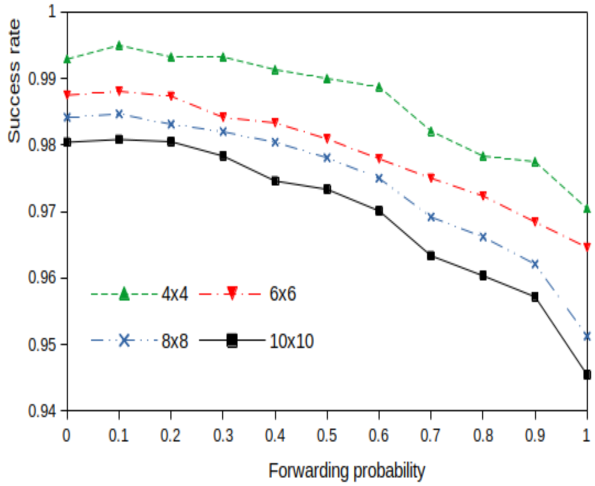


Figure 6.11: Success rate vs. forwarding probability in DPIF in different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Figure 6.11 depicts the correlation between the forwarding probability and the success rate across different network sizes. The success rate remains almost stable when *p* varies from 0 to 0.50 in most network sizes. However, when the forwarding probability surpasses 0.50, the success rate experiences a modest decrease. This observation highlights that a higher forwarding probability does not necessarily ensure a higher success rate. The rise in packet collisions associated with a higher forwarding probability leads to the loss of both interest and data packets, impeding the delivery of interest packets to the producer and data packets to the consumer. These results emphasize the importance of carefully selecting the forwarding probability to balance efficient forwarding with the mitigation of packet loss, as the effectiveness of interest forwarding strategies depends on network conditions.

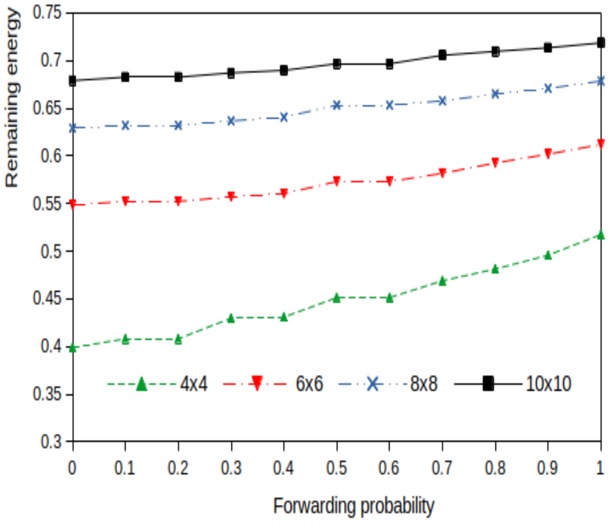


Figure 6.12: Remaining energy vs. forwarding probability in DPIF for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

By examining the relationship between the remaining energy and the forwarding probability, valuable insights can be gained into the energy efficiency of DPIF in NDN over LLNs. Figure 6.12 illustrates an increase in remaining energy, albeit at a slower rate in larger network sizes, with increasing forwarding probability. This trend emphasizes the potential for enhanced energy conservation in the network by selectively forwarding interest packets through probabilities, thereby reducing unnecessary data transmissions and overall energy consumption. These findings highlight the importance of optimizing the forwarding probability parameter to balance efficient data delivery and energy conservation in the context of NDN over LLNs.

Our analysis has unveiled that, relative to the parameter *k*, DPIF exhibits reduced sensitivity to variations in the forwarding probability, *p*, across crucial performance metrics, including the number of retransmitted interest and data packets, as well as remaining energy. Conversely, the retrieval latency and success rate exhibit marginal sensitivity to changes in the forwarding probability. This observation holds practical significance, suggesting that the choice of *p* is less constrained by network characteristics. Based on our findings, we recommend configuring the forwarding probability to *p*=0.50. This specific value effectively balances network performance by maintaining a relatively stable number of sent interest and data packets, while ensuring acceptable data retrieval latency and success rates.

Criterion for dropping interests after the listening period:

In DPIF introduced above, the duplicate control phase involves a node recording the shortest distance to the producer among duplicate packets received during the listening period. If the recorded shortest distance is less than the distance from the current intermediate node to the producer, the node discards the interest packet. This criterion is also employed in the PAF and LFBL. However, in DBF, LAFS, and GOSSIP, an intermediate node utilizes a threshold of received duplicate packets to determine whether to forward or discard an interest packet after the listening period concludes. Upon the expiration of the listening period, an intermediate node tallies the number of duplicate packets received. If this count surpasses a predetermined threshold (*m*), the node discards the interest packet; otherwise, the node proceeds to forward the packet.

Figure 6.13 presents the number of sent interest packets as the threshold varies from 2 to 4 across the four network sizes. The results for DPIF with the distance criterion are included in the figure; they are denoted by "DPIF" on the X-axis of the figure. The results indicate that when the threshold is set to *m*=2, the number of sent interest packets is lower than the other threshold values, *m*=3 or 4, and it is even slightly lower than the number of sent interest packets in DPIF. Similarly, Figure 6.14 shows that the number of sent data packets follows the same performance trends across the four network sizes. As the threshold increases, most intermediate nodes decide not to drop an interest packet but forward it, leading to an increased number of sent interest packets, thus increasing the sent data packets.

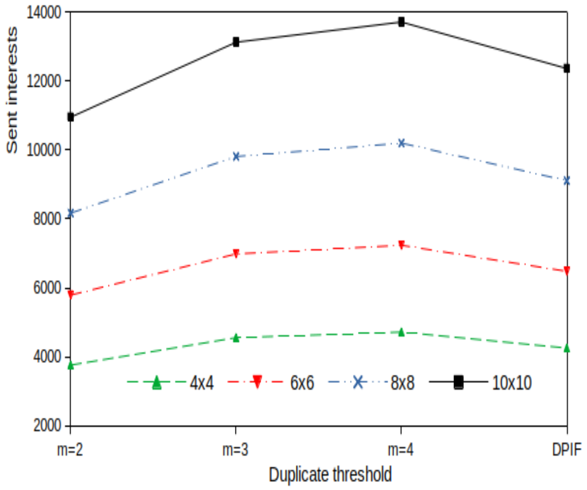


Figure 6.13: Sent interests vs. duplicate threshold for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

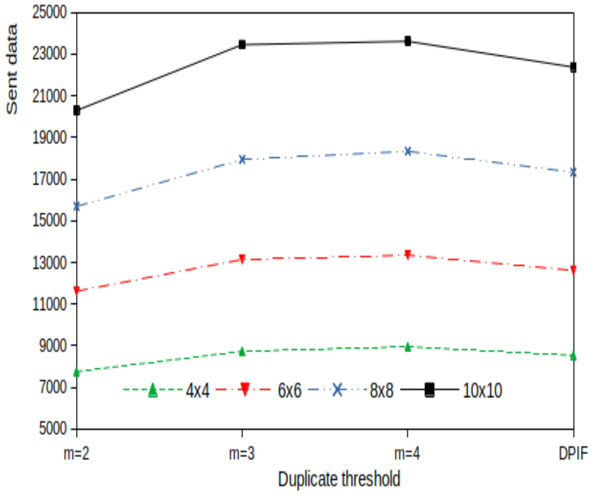


Figure 6.14: Sent data vs duplicate threshold for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Figure 6.15 analyzes the relationship between the retrieval latency and the threshold in the four network sizes. The results demonstrate that DPIF with the distance criterion achieves a lower retrieval latency than the threshold *m*=2, indicating its effectiveness in reducing latency and improving data packet retrieval. However, the latency values for DPIF are comparable to those for thresholds *m*=3 and 4. The lower retrieval latency with increasing threshold values can be attributed to intermediate nodes forwarding more interest and data packets. Notably, when the threshold is *m*=2, nodes drop interest packets even when they are along the shortest path to the producer. Contrarily, relay nodes in DPIF drop interest packets only when they hear a duplicate interest with a shorter distance to the producer during the listening period.

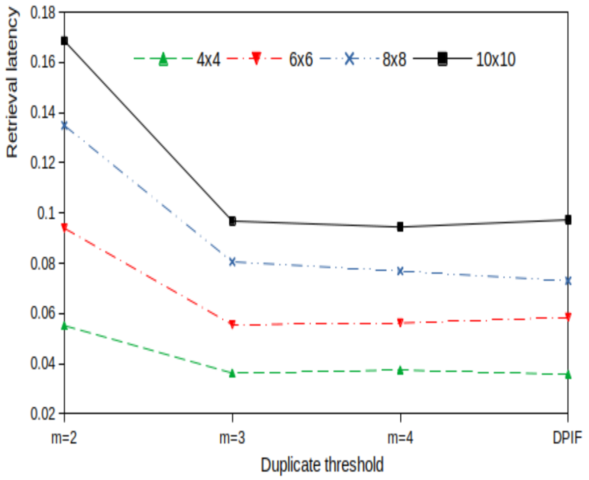


Figure 6.15: Retrieval latency vs. duplicate threshold for different network sizes. The consumer generates 1 interest /s. The consumer/producer speed is 10 m/s.

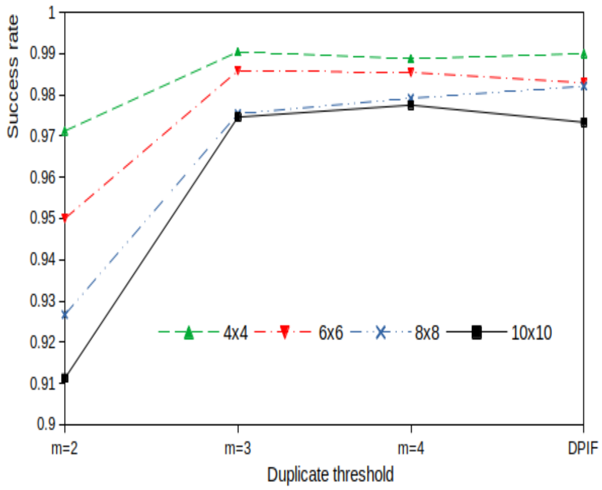


Figure 6.16: Success rate vs. duplicate threshold for different network sizes. The consumer generates 1 interest/s. The consumer/producer speed is 10 m/s.

Figure 6.16 showcases the success rate as the threshold is varied. The results indicate that higher threshold values, *m*=3 and 4, generally lead to higher success rates than a lower threshold value, *m*=2. The observed improvement is due to nodes dropping fewer interest packets due to higher thresholds, thereby enhancing the success rate of data retrieval. Additionally, by adopting the distance criterion for dropping interest packets, DPIF achieves success rates comparable to those achieved by higher threshold values, *m*=3 and 4. DPIF can adjust its interest forwarding behavior to achieve success rates similar to higher threshold values.

Figure 6.17 plots the remaining energy against the threshold values. The graphs exhibit a clear trend, indicating that as the threshold increases, the remaining energy decreases steadily for all network sizes. Additionally, DPIF demonstrates a consistent level of energy consumption between the low threshold value of *m*=2 and higher threshold values of *m*=2 and 3 across all network sizes, highlighting its potential for achieving energy optimization in such networks.

In summary, by leveraging the distance to the producer as a criterion for dropping interest packets, DPIF balances reducing redundant traffic, as evidenced by a lower number of sent interest packets, and maintaining efficient data dissemination. Moreover, DPIF demonstrates favorable retrieval latency, outperforming a threshold-based approach while achieving competitive success rates close to higher threshold values. Additionally, DPIF showcases a reasonable compromise in terms of remaining energy consumption. Overall, these findings highlight the effectiveness of DPIF in achieving a harmonious trade-off among the considered performance metrics.

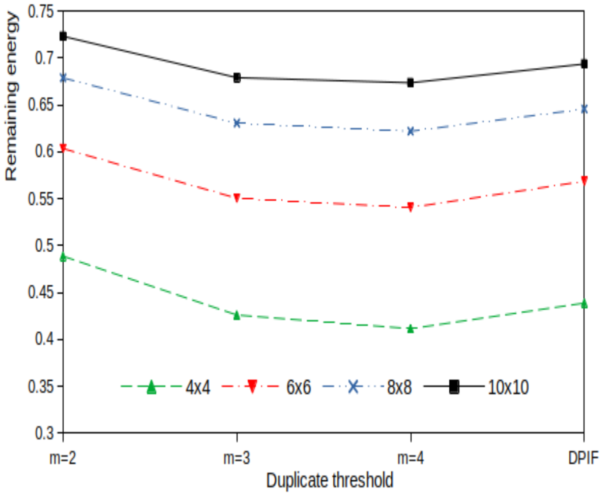


Figure 6.17: Remaining energy vs. duplicate threshold for different network sizes. The consumer generates 1 interest packet/s. The consumer/producer speed is 10 m/s.

6.4 Conclusions

This chapter has tackled the important challenge of enhancing interest forwarding strategies in NDN over LLNs, an area of increasing significance with the proliferation of IoT. Our comprehensive review has revealed that existing strategies employ one or a combination of mechanisms for flooding, forwarding, duplicate, and propagation control. Moreover, our review has also uncovered a common shortcoming among existing strategies—they often incorporate duplicate control but lack propagation control, leading to excessive and unnecessary interest retransmissions. Conversely, the limited number of strategies integrating propagation control exhibit unsatisfactory performance in the presence of producer mobility, primarily due to the absence of flooding control. In response to these identified limitations, this chapter has proposed Distance-based Probabilistic Interest Forwarding (DPIF) which is explicitly designed to assess the effectiveness of combining distance-based propagation control, probability-based forwarding control, and listening periods for duplicate control in NDN over LLNs. Equally important, DPIF integrates flooding control to adeptly manage producer mobility scenarios.

The chapter has conducted a thorough performance analysis to evaluate the impact of critical parameters governing the control mechanisms on the effectiveness of DPIF. Through extensive experimentation, we have determined that the performance of DPIF is significantly impacted by the careful selection of parameters, particularly the number of flooding hops (k) and the forwarding probability (p). Our findings indicate that configuring k=2 and p=0.5 optimally balances the trade-offs between the number of sent interest/data packets, and thus remaining energy and retrieval latency and success rates. Additionally, our analysis has highlighted the advantage of utilizing distance to data producers as a criterion for dropping interest packets after the listening period expiration, as opposed to relying on a threshold for received duplicate packets. This approach has consistently demonstrated superior performance in terms of reducing unnecessary retransmissions and enhancing overall network efficiency.

7. Comprehensive Performance Evaluation of Interest Forwarding Strategies in NDN over LLNs

7.1 Introduction

Existing research, exemplified by [24, 29], has extensively surveyed diverse forwarding strategies designed for NDN over wireless networks, utilizing IEEE 802.11 [22] and IEEE 802.15.4 [4] communication technologies. However, these surveys have primarily concentrated on comparing the "conceptual" aspects of these techniques, lacking a comprehensive performance evaluation under realistic conditions involving heavy traffic loads and diverse mobility scenarios. Moreover, our review of the current research literature indicates that the evaluation of most existing forwarding strategies has predominantly involved comparative analyses against DBF and BF, as illustrated in Table 7.1. Moreover, most existing performance studies [30, 31, 32, 33, 82] have considered either static or mobile scenarios separately, failing to provide comprehensive evaluations encompassing both conditions. This limitation results in a notable knowledge gap regarding the relative performance of these strategies in stationary versus mobile settings. Addressing this gap, this chapter presents one of the first comprehensive performance evaluations of major forwarding strategies proposed for NDN over LLNs. Our analysis spans diverse network configurations and dynamic operating conditions, aiming to provide novel insights into the performance behavior of these strategies.

Table 7.1: Examples of interest forwarding strategies, listed alphabetically, and those compared against in existing performance evaluation studies and the scenarios considered in the evaluation.

Forwarding strategy	Compared against	Static/mobile scenario
DMIF [32]	BF, PAF[28]	Static
LAFS [31]	BF, DBF [30]	Static
PAF [28]	DBF[30]	Mobile
RLF [33]	BF, RONR [26]	Static

Our discussion will focus on the following seven strategies (in alphabetical order): BF, DBF, DPIF, GOSSIP, LAFS, PAF, and PF. The rationale behind selecting these strategies is twofold. Firstly, this study marks the first attempt to explore the efficacy of probabilistic solutions for interest forwarding in NDN over LLNs. PF and GOSSIP are included in our performance analysis because, despite extensive investigations into their performance behavior in MANETs and WSNs, their application in the context of NDN over LLNs remains unexplored. Furthermore, DPIF employs flooding, forwarding, and duplicate control mechanisms akin to GOSSIP, making it compelling to quantify DPIF's performance advantage over GOSSIP. Secondly, other strategies such as LAFS and PAF represent some of the primary "conceptual" approaches adopted by most research endeavors to address the interest forwarding problem in NDN over LLNs. For instance, LAFS enhances both RONR and DMIF to accommodate mobility, while PAF adapts LFBL to align with NDN architecture specifications. Additionally, PAF exemplifies strategies that maintain distance tables, including LFBL, NAIF, and R-LF. Finally, DBF and BF are included in our study for completeness, serving as fundamental references against which to evaluate the effectiveness of competing forwarding strategies, including DPIF.

The subsequent sections of this chapter are structured as follows. Section 7.2 outlines the simulation model and system parameters employed in our performance evaluation. Subsequently, this section presents the performance results. Section 7.3 discusses the general performance trends. Finally, Section 7.4 concludes the chapter.

7.2 Performance evaluation

In a recent development, an effort was made to construct an analytical model for NDN over LLNs [97]. However, the scope of this model was confined to estimating the success rate of the BF strategy exclusively. Given the intricate nature of developing analytical models for alternative forwarding strategies such as DPIF, DBF, GOSSIP, LAFS, and PAF, simulation emerges as the sole viable approach to comprehensively assess the performance of forwarding strategies in the context of NDN over LLNs. To conduct our thorough evaluation study, we have implemented DPIF, GOSSIP, and PF in ndnSIM v2.8 [90]. Additionally, we have integrated the existing forwarding strategies, including DBF, LAFS, and PAF, to benchmark their performance against our proposed solutions. It is worth noting that BF, often referred to as the "multicast" forwarding strategy [90], is implemented by default in ndnSIM. The simulation model is based on the same assumptions outlined in Chapter 5, and these are restated below for the sake of completeness.

- Nodes form an *n*x*n* square grid topology. Neighboring nodes along the X and Y dimensions can communicate with each other. Nonetheless, communication along the diagonal is not possible due to the longer diagonal distance than the distance along X/Y dimensions.
- Consumer and producer nodes move within the square topology using the random waypoint model [91]. Consumers generate interest packets at a constant rate. The interest packets are independent of each other and have a fixed length. Furthermore, producers generate data packets upon receiving interest packets. The data packets have a fixed length.
- The NDN layer in an intermediate node uses the service provided by the IEEE 802.15.4 data link layer to transfer physically interest and data packets to the one-hop neighboring nodes. The MAC sublayer employs the unslotted CSMA/CA algorithm of the IEEE 802.15.4 standard with the default settings [4]. The PHY sublayer of the IEEE 802.15.4 introduces no transmission errors. However, packets can be lost due to packet collision, which occurs when adjacent nodes transmit packets simultaneously.

- The processing time of interest or data packets due to the protocol stack in a given node is negligible.
- No faults occur in the network, and nodes never run out of battery power.

In the results reported in the figures below, unless stated otherwise, the forwarding probability in DPIF has been fixed at *p*=0.50. This value has been selected because it enables DPIF to exhibit the best performance tradeoffs compared to other probability settings, as has been demonstrated in the preceding Chapter 6. Moreover, the forwarding probability for PF and GOSSIP has been set to *p*=0.85 and *p*=0.65, respectively, since Chapter 5 has revealed that such probability values permit these strategies to achieve good performance tradeoffs between retransmitted packets, overall retrieval latency, and success rates.

The listening period in DPIF, DBF, GOSSIP, DBF, and LAFS is uniformly distributed over 20 milliseconds. On the other hand, a given node in PAF uses one of three listening periods depending on its distance from the producer. The listening period is uniformly distributed between 0 and 15 if the interest packet is within four hops away from the producer and between 0 and 20 if it is within eight hops away. Finally, it is between 0 and 25 if it is over eight hops away. The threshold for duplicate interest packets in DBF, GOSSIP, and LAFS is 2. Table 7.2 summarizes the main parameters utilized in our simulations; such parameters and their associated values have been widely employed in similar research studies [26-32, 51].

We have collected extensive statistics for the following performance metrics, widely adopted in similar performance evaluation studies [26-32, 51].

- ***Sent interests:*** The total number of interest packets transmitted by the network nodes during the simulation time.
- ***Sent data:*** The total number of data packets transmitted by the network nodes during the simulation time.
- ***Retrieval latency:*** the time an interest packet takes to arrive at a producer plus the time a data packet takes to arrive at a consumer. An average is computed over all interest packets generated by the consumer.
- ***Success rate:*** the number of data packets successfully received by the consumer over the number of interest packets generated in the network.
- ***Remaining energy:*** The energy that remains in a node's battery at the end of the simulation over the initial energy available at the start of the simulation. An average is computed over all the network nodes.

This section conducts a comparative analysis of BF, DBF, DPIF, GOSSIP, LAFS, PAF, and PF, across diverse scenarios. The evaluation is designed to scrutinize their performance across varying network sizes, adaptability to different consumer and producer speeds, and efficiency in handling concurrent data requests when multiple consumer-producer pairs coexist in the network. Through these comprehensive evaluations, valuable insights into the strengths and weaknesses of each forwarding strategy under a spectrum of network conditions will be gained. The findings will provide valuable recommendations for efficient interest forwarding in NDN over LLNs.

Table 7.2: Summary of the main parameters and values used in the simulation.

Parameters	**Values**
MAC Protocol	IEEE 802.15.4
Transmission range (m)	50
Link bandwidth (Kbps)	250
Topology	Square grid
Listening period (of Δ milliseconds) in DBF, DPIF, GOSSIP, and LAFS	Uniformly distributed from 0 to 20
Flooding hops in DPIF and GOSSIP	2
Duplicate threshold for DBF, GOSSIP, and LAFS	2
Update period (of ρ seconds) for DPIF, LAFS, and LAFS	2
Interest generation rate (packets/s)	1
Number of consumers	1
Number of producers	1
CS size (number of packets)	8
PIT size (number of entries)	8
Interest size (bytes)	10
Data payload (bytes)	10
Initial energy of the battery (Joules)	20
Simulation time (s)	400

7.2.1 Impact of network size

This set of simulation experiments examines four network sizes, notably 4x4, 6x6, 8x8, and 10x10 nodes. The experiments involve a consumer and a producer, which move at a speed of 10 m/s. Moreover, the consumer generates one interest packet per second. Figure 7.1 presents the number of interest packets sent by the seven forwarding strategies when deployed over four network sizes. As the network size increases, the number of sent interest packets increases due to the increase in the number of hops that interest packets have to make to reach the producer. DPIF has a slightly better performance than PAF. However, it has a noticeably better performance than the remaining strategies. In addition, DBF, GOSSIP LAFS, and PF have a comparable number of sent interest packets. However, these four strategies send much more interest packets than DPIF. As expected, BF has the highest number of sent interest packets. DPIF and PAF have a lower number of sent interest packets since they employ multiple control mechanisms for interest forwarding. First, a given relay node applies propagation control to drop interest packets if the node is not an eligible forwarder due to its longer distance to the producer than its one-hop neighbors. Second, a relay node applies duplicate control to remove duplicate interest packets. In contrast, the other forwarding strategies rely on a single control mechanism to reduce interest forwarding. More specifically, DBF, GOSSIP, and LAFS employ duplicate control, whereas PF employs s probability-based forwarding control to reduce the number of sent interest packets.

Figure 7.2 reports the number of sent data packets in the different forwarding strategies. As expected, the number of sent data packets increases as the network size increases. The findings indicate that DPIF has the lowest number of sent data packets compared to the other strategies. Following in ascending order, PAF, PF, BF, GOSSIP, LAFS, and DBF have progressively higher numbers of sent data packets. DPIF performs exceptionally well regarding the number of sent data packets due to its ability to minimize the retransmission of interest packets, as demonstrated in Figure 7.1. Following the NDN paradigm, data packets take the reverse path formed by interest packets while searching for the producer. By transmitting the lowest number of interest packets, DPIF ensures that interest packets visit a lower number of intermediate nodes during their network journey. This reduces the number of intermediate nodes visited by data packets, lowering the number of sent data packets inside the network.

PAF exhibits more sent data packets than DPIF but less than the remaining strategies in large network sizes. This is due to its reliance on the same distance-based propagation and duplicate control mechanisms as DPIF to lower the number of sent interest packets within the network, thus reducing the number of intermediate nodes that retransmit data packets. PF has more sent data than DPIF and PAF but is less than GOSSIP, LAFS, and DBF. This is because nodes drop interest packets based on probabilistic decisions. Moreover, the lack of duplicate control in PF increases the chance of interest packets experiencing collisions. These two factors result in interest packets visiting a lower number of intermediate nodes, leading to PF having a lower number of sent data packets.

Although DBF lowers the number of duplicated interest packets through listening periods, it lacks a propagation control mechanism. As a result, most interest packets wander throughout the network and consequently visit many intermediate nodes, resulting in DBF having more sent interest packets. Consequently, data packets visit many intermediate nodes during their reverse journey back to the consumer, resulting in DBF having the highest number of sent data packets. It is worth mentioning that LAFS has the second-highest number of sent data packets after DBF. This is because intermediate nodes in LAFS alternate between the BF and DBF forwarding modes. Suppose an intermediate node receives a marked interest packet because a data packet generated by the producer has already passed through the intermediate node. In this case, the intermediate node employs DBF to reduce the number of duplicate interest packets—otherwise, the node resorts to BF. Moreover, GOSSIP has the third highest number of sent data packets since it alternates between BF and DBF through a probabilistic mechanism.

Figure 7.3 shows that the retrieval latency increases linearly with the network size across the forwarding strategies due to the increase in the number of hops an interest/data packet makes to cross the network. GOSSIP has the lowest retrieval latency as the network size increases. This is because 65% of the interest packets passing through a given node bypass the duplicate control mechanism as the forwarding probability is set to $p=0.65$. BF has the second lowest latency in the 8x8 and 10x10 networks due to the large number of interest packets BF uses to search for the producer throughout the network and the large number of data packets used to reach the consumer during the reverse journey. Moreover, relay nodes in BF promptly retransmit any received interest packets without going through a listening period. DPIF has a higher retrieval latency than GOSSIP and BF but lower than DBF, LAFS, PAF, and PF. The retrieval latency in PF is the highest since relay nodes may drop interest packets based on probabilistic decisions. Thus, the consumer has to reissue another copy of the interest to start the search for the producer from scratch, increasing the retrieval latency. PAF has the second higher retrieval latency since each interest packet has to go through duplicate control at each hop, and the duration of the listening period scales with the distance to the producer.

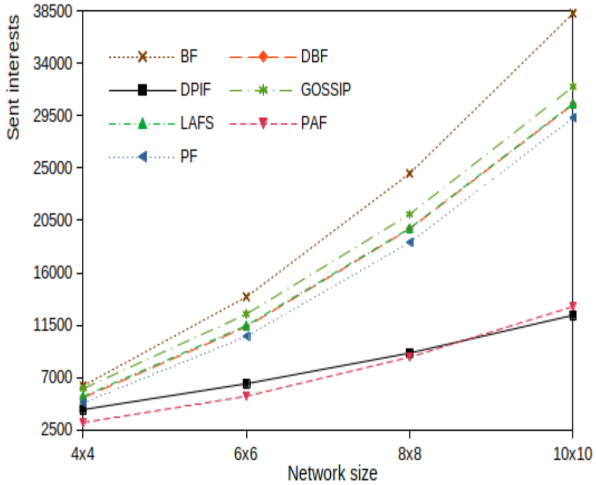


Figure 7.1: Sent interests vs. network size in the seven forwarding strategies. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

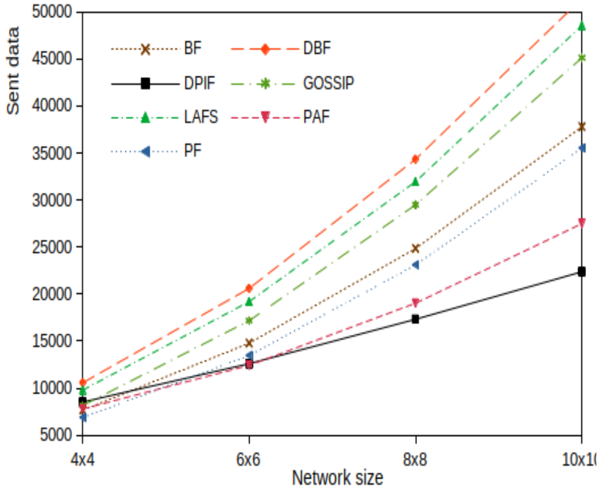


Figure 7.2: Sent data vs. network size in the seven forwarding strategies. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

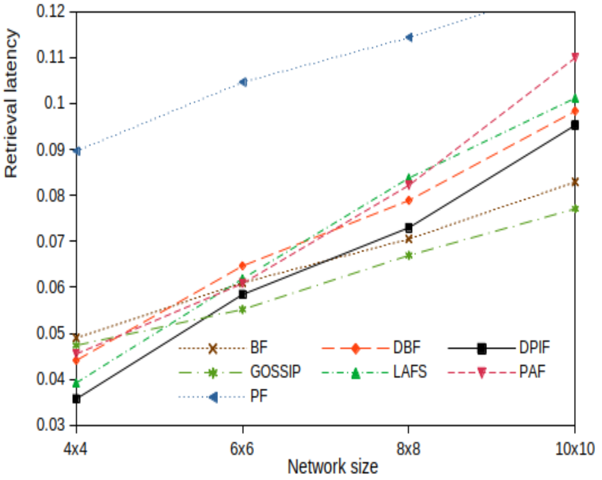


Figure 7.3: Retrieval latency vs. network size in the seven forwarding strategies. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

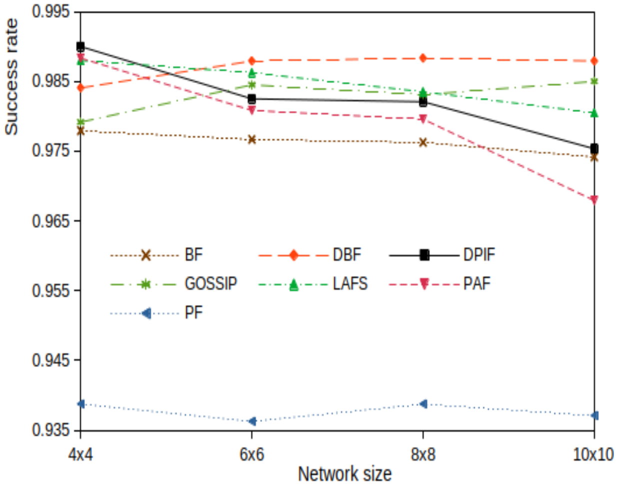


Figure 7.4: Success rate vs. network size in the seven forwarding strategies. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

Figure 7.4 provides insight into the success rate across the different forwarding strategies. The results reveal that the success rate remains consistent across the seven forwarding strategies as the network increases. However, it is worth noting that the success rate is relatively high (over 97.5%) for all the forwarding strategies, apart from PF, which has the lowest success rate, below 94%. On the other hand, BF, DPIF, PAF, and GOSSIP have comparable success rates of around 98%. DBF achieves the highest success rate of 99%. Interestingly, DPIF has a success rate of only 1.5% lower than that of DBF. However, DBF achieves this high success rate at the cost of transmitting more interest and data packets, as shown in Figures 7.1 and 7.2.

The high success rate achieved by most forwarding strategies in the presence of mobility can be attributed to several factors. Consumers and producers visit new network regions when they move across the grid topology, allowing interest packets to explore new alternative paths that may have a relatively lower traffic load. As a result, interest packets can reach the producer through different routes, increasing the success rate. Moreover, mobility causes the consumer and producer nodes to get close to each other for a given period. As a result, packets travel shorter distances to cross the network. This reduces the probability of packet collisions and enables many interest packets (and data packets) to reach the producer (and consumer). In contrast, in the absence of mobility, interest and data packets always travel through the same paths, competing for the same network resources (e.g., channels), resulting in higher packet collisions and, therefore, resulting in a lower success rate. Overall, Figures 7.1, 7.2, and 7.4 suggest that DPIF can achieve high success levels comparable to the other forwarding strategies while reducing the number of sent interest and data packets.

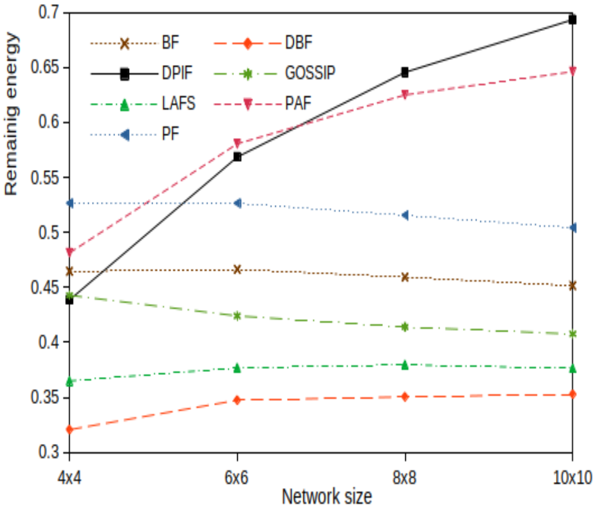


Figure 7.5: Remaining energy vs. network size in the seven forwarding strategies. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

Finally, Figure 7.5 shows the remaining energy as a function of the network size. Our findings reveal that as the network size increases the remaining energy remains unchanged in BF, DBF, GOSSIP, and LAFS, but it is lower than in DPIF and PAF. In contrast, the remaining energy increases with the network size in DPIF and PAF. Specifically, in a 10x10 network, DPIF exhibits the highest remaining energy of nearly 70%, while PAF is lower at 64%, a difference of 6% compared to DPIF. PF has remaining energy at 50%, followed by BF and GOSSIP at 45% and 40%, respectively. The cause of DPIF's higher remaining energy is due to its lower number of sent interest and data packets compared to the other forwarding strategies. Conversely, DBF and LAFS have the lowest remaining energy at 35% and 37%, respectively, due to their highest number of sent interest and data packets.

7.2.2 Impact of mobility

This second set of experiments assesses the effects of mobility on system performance. The speed of the consumer and producer is varied in the 10x10 network from 0 (i.e., static scenario) to 30 m/s. The consumer generates one interest per second. Based on the findings depicted in Figure 7.6, as the consumer and producer speed increases, DPIF consistently exhibits superior performance by reducing the number of sent interest packets compared to the other strategies. DPIF achieves this efficiency through its unique combination of flooding, propagation, forwarding, and duplicate control mechanisms, optimizing the utilization of network resources. More crucially, flooding control ensures careful dissemination of interest packets in the network, enabling effective tracking of the mobile producer. Although PAF also outperforms the other strategies, it falls behind DPIF. This discrepancy is due to the lack of a flooding control mechanism in PAF, resulting in a marginally higher number of sent interests. The number of sent interests in PF, DBF, LAFS, and GOSSIP is considerably higher than in DPIF and PAF. This is because they employ only the duplicate control mechanism, but they still forward interest packets across all network directions without any propagation control. Notably, BF has the highest number of sent interest packets as it does not use any mechanism to refrain from interest retransmissions.

Figure 7.7 illustrates the number of sent data packets for each forwarding strategy at varying speed values. DPIF consistently demonstrates a lower number of sent data packets throughout the speed range compared to the other strategies. The disparity between DPIF and PAF is notably more pronounced regarding sent data packets than the sent interest packets, as depicted in Figure 7.6. Furthermore, the following interesting performance trend can be noticed in Figure 7.7. The strategies that incorporate duplicate control, such as DBF, LAFS, PAF, and GOSSIP, exhibit a higher number of sent data packets in contrast to techniques like BF and PF, which do not employ duplicate control. DBF, LAFS, PAF, and GOSSIP eliminate duplicate packets from the network during a designated time frame, thereby reducing redundant traffic and conserving network resources. Consequently, interest packets can traverse the network for extended periods without experiencing collisions. However, since these strategies do not employ propagation control, interest packets may roam within the network until their interest lifetime expires and are subsequently removed. Following the NDN paradigm, data packets follow the path initially established by interest packets. As a result, intermediate nodes that interest packets have visited may retransmit data packets, contributing to the higher number of sent data packets being observed in these strategies. On the other hand, PF uses probabilities for forwarding control, while BF floods interest packets in the network. These two strategies do not actively remove duplicate packets. As a result, interest packets are more likely to encounter collisions and, thus, do not progress further in the network. Consequently, interest packets in PF and BF visit a relatively lower number of intermediate nodes. This results in PF and BF data packets visiting a lower number of intermediate than in DBF, LAFS, and GOSSIP.

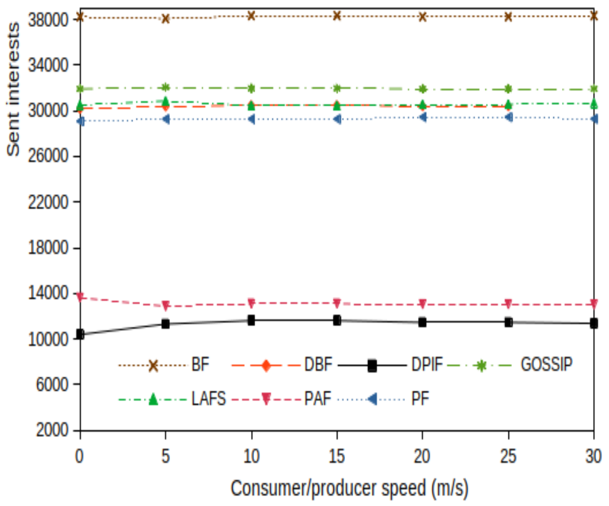


Figure 7.6: Sent interests vs. consumer and producer speed in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s.

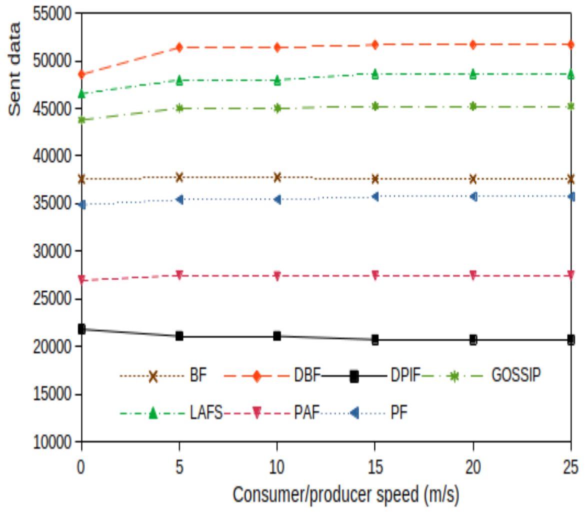


Figure 7.7: Sent data vs. consumer and producer speed in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s.

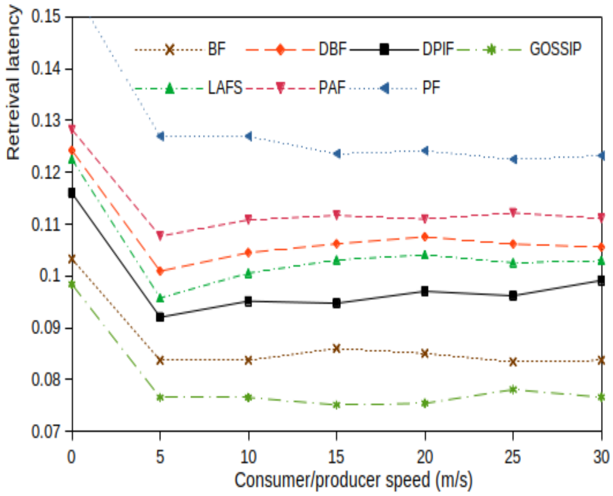


Figure 7.8: Retrieval latency vs. consumer and producer speed in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s.

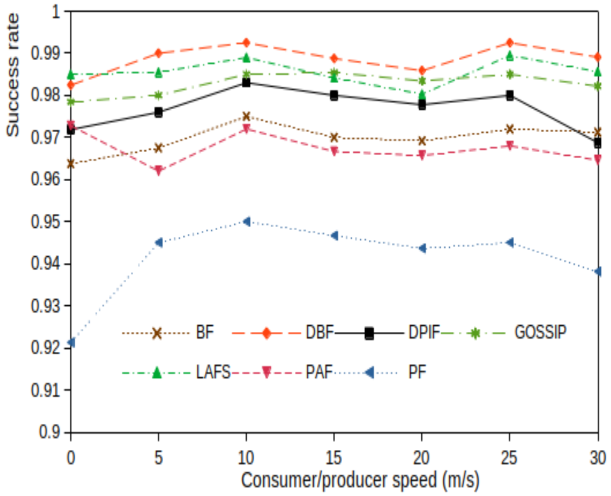


Figure 7.9: Success rate vs. consumer and producer speed in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s.

Figure 7.8 illustrates the effect of increasing consumer speed on the retrieval latency in NDN over LLNs. Interestingly, the relative performance ranking of the seven forwarding strategies remains consistent regardless of the consumer and producer speeds. DPIF exhibits a higher retrieval latency than GOSSIP and BF but lower than LAFS, DBF, PAF, and PF. Among the strategies, GOSSIP achieves the lowest retrieval latency due to 65% of the interest packets bypassing duplicate control and being promptly retransmitted by intermediate nodes. This reduces the transit time from consumer to producer. Additionally, the listening period in GOSSIP helps reduce packet collisions, enabling interest and data packets to traverse the network without experiencing collisions. BF also exhibits a relatively lower retrieval latency due to its uncontrolled flooding strategy and the absence of a listening period. Still, this advantage comes at the cost of more sent interest packets, as observed in Figure 7.6. On the other hand, DPIF demonstrates higher retrieval latency than GOSSIP and BF due to its utilization of listening periods. LAFS exhibits higher latency than DPIF since more packets go through duplicate control. DBF experiences higher retrieval latency as all interest packets must undergo the listening period. PAF also demonstrates high latency as interest packets may encounter longer listening periods when situated farther from the producer. Lastly, PF exhibits the highest retrieval larceny among the strategies due to the random dropping of packets by intermediate nodes. This forces the consumer to issue new copies of interest packets if data packets are not received within a specified timeout interval.

Figure 7.9 indicates that PF suffers the worst success rate since it drops interest packets randomly to reduce redundant packet retransmissions. Even though 85% of the interest packets in PF are forwarded by intermediate nodes, and thus only 15% are dropped, this negatively impacts the achieved success rate in PF. PAF also has a lower success rate than the other strategy since interest packets further away from the producer are constantly dropped due to distance-based propagation control. However, due to node mobility, interest packets judged by a given intermediate node to be far from its distance to the producer can become close due to the producer's constant mobility. Furthermore, we notice that when the consumer and producer are static (i.e., speed =0), the success rate of PAF is comparable to that of DPIF since intermediate nodes always make a sound judgment about the proximity of interest packet as far as producers are concerned since the latter is stationary, and thus does not change location. BF also exhibits a lower success rate than DPIF and the other listening-based forwarding techniques because of the higher packet collisions to the redundant interest retransmissions without any control mechanism to reduce superfluous interest retransmissions. To sum up, DPIF offers a good performance tradeoff among the strategies that employ duplicate control since it manages to achieve a success rate that is lower by only 1% compared to DBF, LAFS, and GOSSIP while achieving better performance than these strategies as far as the other performance metrics are concerned.

Figure 7.10 depicts the performance of the seven forwarding strategies regarding the remaining energy. DPIF significantly reduces the number of sent interest and data packets, reducing energy consumption, and resulting in higher remaining energy levels than other strategies. Similarly, PAF demonstrates relatively higher remaining energy levels, although lower than DPIF. On the other hand, PF achieves relatively higher remaining energy than BF, LAFS, DBF, and GOSSIP due to its probabilistic forwarding mechanism, which reduces the number of sent interest packets. However, this energy-saving feature comes at the expense of higher retrieval latency and lower success rate, as indicated by Figures 7.8 and 7.9, respectively. Interestingly, BF exhibits higher remaining energy than the strategies solely employing duplicate control, such as LAFS, DBF, and GOSSIP. This is because although BF has the highest number of sent interest packets, it has a much lower number of sent data packets than DBF, GOSSIP, and LAFS, as revealed in Figure 7.7. Consequently, the total number of sent interest and data packets in these listening-based strategies is higher than in BF, resulting in increased energy consumption and reduced remaining energy levels. Finally, DBF demonstrates the lowest remaining energy among the strategies, primarily because it has the highest number of sent interest and data packets.

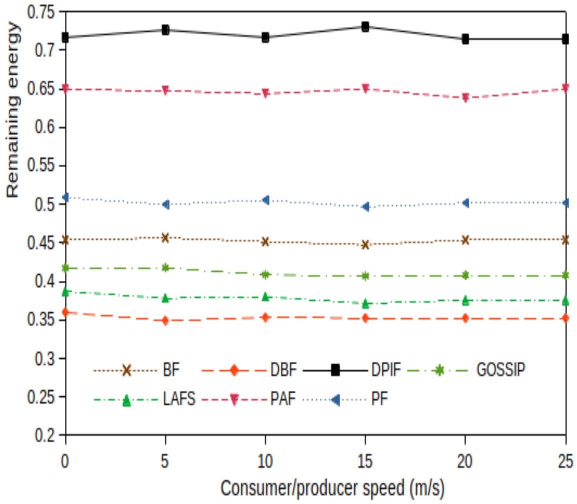


Figure 7.10: Remaining energy vs. consumer and producer speed in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s.

7.2.3 Impact of multiple consumer-producer pairs

The impact of multiple consumer-producer pairs on system performance is evaluated in this final set of experiments. The speed of both the consumer and producer nodes is set at 10 m/s in the 10x10 network. Each consumer generates a different name prefix at a rate of one interest/s. The general conclusions have been found to stay the same when other network sizes and traffic generation rates are considered.

Figure 7.11 illustrates the relationship between the number of consumer-producer pairs and the sent interest packets. As the number of consumer-producer pairs increases, as expected, the number of sent interests increases across the different forwarding strategies. BF floods the network with interest packets, resulting in a consistent increase in sent interest packets as the number of pairs grows. On the other hand, DBF reduces unnecessary interest retransmissions by implementing duplicate control but still shows a notable increase in sent interest packets. DPIF stands out with a lower number of sent interest packets compared to the other strategies due to its effective control mechanisms. PAF has a slightly higher number of sent interests than DPIF, as it does not have a flooding phase to enable interests to propagate into the network. Instead, interests die out during their network journey, and thus, consumers are forced to re-issue new interest packets, thus increasing the sent interest packets.

PF has a lower number of sent interest packets since relay nodes probabilistically drop interest packets. Even when consumers regenerate new interest packets after a timeout before data packets reach the consumers, intermediate nodes still drop these packets probabilistically. The performance difference between DBF and GOSSIP in favor of DBF becomes more noticeable as the number of consumer-producer pairs increases. This performance behavior could be explained by the fact that 65% of the interest packets in

GOSSIP bypass the listening period, and thus are transmitted immediately by relay nodes. This increases the likelihood of packet collisions. Consequently, consumers are forced to regenerate new interest packets to request data from producers. Another noticeable trend revealed by this figure is that the LAFS worsens and approaches that of BF when the number of consumer-producer pairs increases. This trend can be explained by the fact that when the number of consumer-producer pairs rises with each pair using a different name prefix, more interest packets are flooded, as happens in BF, by intermediate nodes due to data packets not passing across those nodes.

Figure 7.12 examines the behavior of the forwarding strategies in terms of the sent data as a function of the number of consumer-producer pairs. DPIF stands out with a relatively lower amount of sent data packets than the other strategies across all the consumer-producer pair scenarios, whereas DBF has the highest amount of sent data packets. The relative performance merits of the other strategies are similar to those already reported above in Figure 7.7. However, one notable difference between Figures 7.7 and 7.12 is that LAFS has a lower number of sent data than GOSSIP, yet it is comparable to that of BF. This phenomenon is due to the considerable number of interest packets being flooded by intermediate nodes without going through duplicate control. Consequently, interest packets are more likely to experience collisions and do not progress farther inside the network. Accordingly, data packets in LAFS visit a lower number of intermediate nodes than in GOSSIP.

For the retrieval latency, Figure 7.13 reveals that the relative performance merits of the forwarding strategies when there are two consumer-producer pairs are comparable to those when there is one consumer-producer pair. However, when there are three consumer-producer pairs, the performance of BF degrades and becomes worse than that of the other strategies, except for PF, which exhibits the highest retrieval latency. When the consumer-producer pairs reach four, the performance of BF suffers the worst degradation due to the increase in packet collisions. Furthermore, the retrieval latency of GOSSIP and LAFS becomes higher than that of DPIF and PAF due to the rise in the larger number of interest packets flooded in GOSSIP and LAFS. Thus, they are more likely to experience collisions. DBF consistently maintains the lowest latency for all the consumer-producer pairs because it reduces network congestion since all interest packets must go through duplicate control. Consequently, duplicate packets are removed from the network, and more importantly, data packets have less chance to collide with interest packets as the listening period helps to introduce more randomization in the access to the shared wireless medium. DPIF has the lowest retrieval latency after DBF due to its ability to reduce traffic in the network due to its efficient forwarding mechanism.

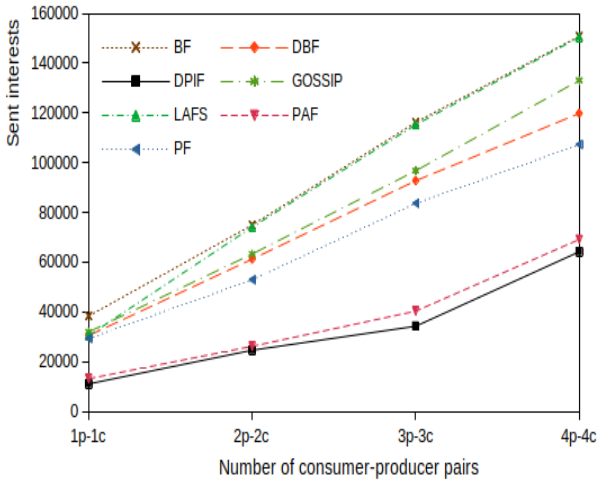


Figure 7.11: Sent interests vs. number of consumer-producer pairs in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

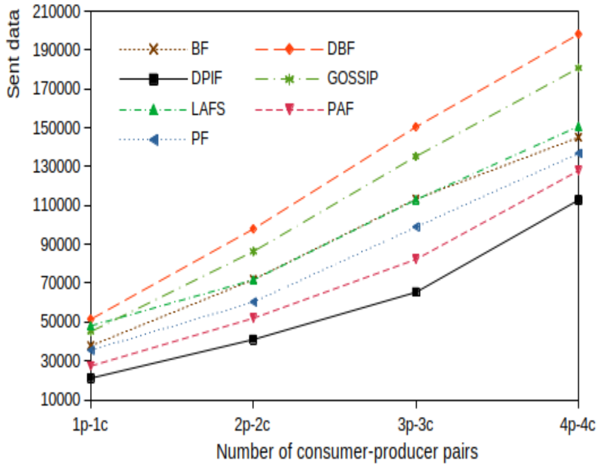


Figure 7.12: Sent data vs. number of consumer-producer pairs in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

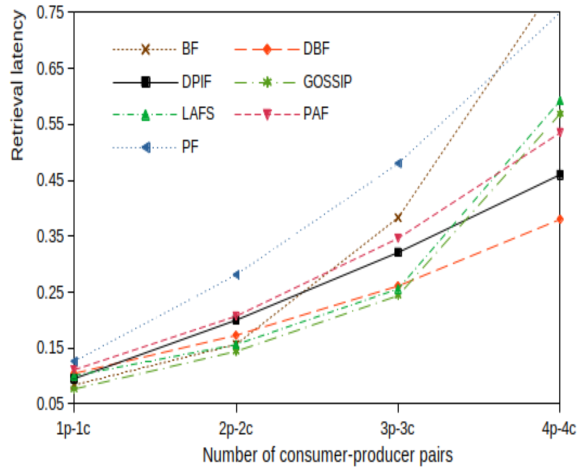


Figure 7.13: Retrieval latency vs. number of consumer-producer pairs in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

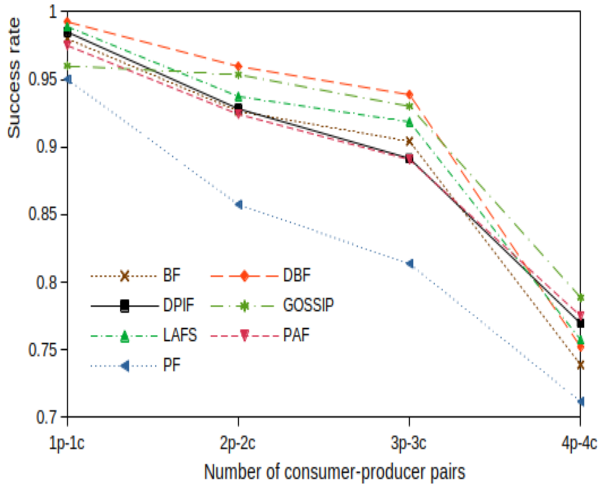


Figure 7.14: Success rate vs. number of consumer-producer pairs in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

Figure 7.14 reveals a clear trend of decreasing success rates with increasing consumer-producer pairs across all the forwarding strategies. This suggests that successfully delivering data to consumers becomes more challenging as the network becomes more congested due to more consumer-producer pairs. BF and DBF initially demonstrate high success rates for a small number of pairs, but as the number increases, their success rates start to decline noticeably. This indicates that these two strategies struggle to handle the increased traffic and data delivery demands when the network becomes more congested with interest packets due to the presence of multiple consumers. In contrast, PF suffers the highest decrease in the success rate due to its random approach to dropping interest packets. DPIF, PAF, GOSSIP, and LAFS also experience a significant decrease in success rates as the number of consumer-producer pairs increases. These strategies, which employ various control techniques to optimize forwarding and reduce redundancy, still face challenges in maintaining high success rates in highly congested network scenarios.

As the number of consumer-producer pairs increases, the remaining energy decreases in all the forwarding strategies, as illustrated in Figure 7.15, indicating higher energy consumption and depletion of resources in the network. As consumer-producer pairs increase, BF, DBF, and LAFS decrease in remaining energy. These strategies, which involve more widespread interest and data dissemination, tend to consume more energy due to the absence of propagation control. DPIF, GOSSIP, PAF, and PF also show a decreasing trend in remaining energy, although at a relatively slower rate than BF, DBF, and LAFS. These strategies leverage various techniques such as distance-based propagation, gossip-based dissemination, and probabilistic forwarding to reduce redundant transmissions and conserve energy. DPIF still exhibits the highest remaining energy in the presence of increased traffic due to the multiple consumer-producer pairs. This performance advantage can be attributed to its efficient flooding and propagation control mechanisms. Our findings highlight the importance of energy-efficient forwarding techniques to prolong the network's operational lifetime and mitigate energy depletion.

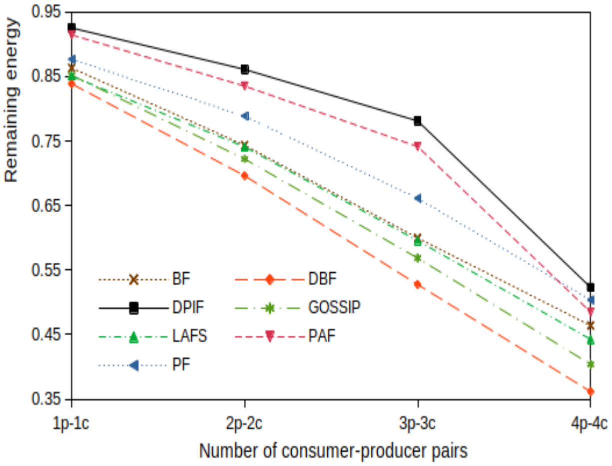


Figure 7.15: Remaining energy vs. number of consumer-producer pairs in the seven forwarding strategies in the 10x10 network. The consumer generates 1 interest/s. The consumer and producer speed is 10 m/s.

7.3 Discussions

Our extensive analysis has consistently revealed a pattern of performance degradation across interest forwarding strategies as network size increases. This is primarily due to the growing challenge of efficiently locating data producers within larger networks. The increase in network size introduces numerous nodes and potential paths for interest packets, leading to a rise in interest and data retransmissions. Consequently, this contributes to increased retrieval latency, making it more challenging for interest packets to reach data producers and data packets to reach consumers promptly. Additionally, success rates are adversely affected by a higher likelihood of packet collisions resulting from extended paths in larger networks. The increased distance between consumers and producers introduces more opportunities for contention, resulting in a decline in the success rate of interest and data packets reaching their intended destinations.

However, the DPIF strategy still exhibits distinct advantages in larger networks, effectively mitigating some of these challenges. For instance, the integration of the flooding control phase enhances the efficiency of interest packet dissemination. Moreover, by strategically combining its four control mechanisms, DPIF achieves performance tradeoffs by significantly minimizing interest and data retransmissions. This optimization not only maximizes remaining energy but also ensures acceptable levels of retrieval latency and success rates. Tables 7.3 and 7.4 provide specific concrete examples of the relative performance merits of DPIF against the other strategy in a 10x10 network with one consumer generating one interest/second. The values in these tables were computed by determining the performance difference between DPIF and each alternative forwarding strategy. This difference was then normalized by dividing it by the performance of the respective forwarding strategy and multiplied by 100 to express it as a percentage. A positive percentage signifies a performance improvement, while a negative percentage denotes a performance degradation.

Table 7.3 illustrates that DPIF demonstrates a remarkable reduction in interest and data retransmissions, surpassing 67% and 59% compared to BF and DBF, respectively. Consequently, DPIF achieves substantial energy savings, exceeding 53% and 86% compared to these strategies, with an even more pronounced advantage over GOSSIP and LAFS. In terms of retrieval latency, DPIF attains lower latency than DBF, LAFS, PAF, and PF, with only a slight increase, not exceeding 19% and 14.8%, compared to GOSSIP and BF, respectively. Moreover, the success rate of DPIF is only marginally lower, by less than 1.2% compared to DBF and below even 1% compared to the other strategies.

It is noteworthy that increasing the number of hops to three (k=3), as shown in Table 7.4, narrows the difference in response latency to 10% and 7% compared to GOSSIP and BF. This adjustment in DPIF still results in a substantial reduction of over 50% in the number of sent interest and data packets, translating to over 45% in energy savings compared to most other strategies. However, this comes at the cost of a slight increase in the number of sent interests, by 13% compared to DPIF with k=2, and 9.4% compared to PAF.

The above finding highlights the delicate performance trade-offs that must be carefully managed, emphasizing the importance of careful tuning of critical parameters—specifically, the number of flooding hops (k) and the forwarding probability (p)—to optimize DPIF performance in real-world scenarios. In light of our findings, we recommend configuring k=2 and p=0.5. This configuration enables DPIF to consistently demonstrate competitive performance in key performance metrics, including packet retransmissions, retrieval latency, success rates, and energy savings.

It is important to note that our observations regarding the performance attributes of the different forwarding strategies remain consistent when mobility speed varies. Regarding node density, our study employs a square grid topology, where each node has four immediate neighbors, except for edge nodes with two neighbors. Consequently, node density remains constant despite variations in network size. The rationale for adopting the square grid topology lies in alignment with the settings of existing research works on LAFS and R-LF. Consistency with established assumptions ensures the equitable comparison of our findings with established studies. Nevertheless, it is crucial to acknowledge that practical real-world deployments of NDN over LLNs may feature more intricate topologies (e.g., unstructured and random), diverse mobility patterns (e.g., random walk), and varied traffic generation patterns (e.g., batch and variable bit generation rates). While our performance analysis offers valuable insights within the adopted assumptions, we acknowledge the need for caution when extrapolating our findings to scenarios with differing characteristics.

Table 7.3: Comparative performance evaluation of DPIF-*k*=2 against the forwarding strategies in the 10x10 network with the consumer generating 1 interest/s. Positive percentages indicate improvement while negative percentages indicate degradation in the performance of DPIF relative to the other strategies.

Performance Metrics	BF	DBF	GOSSIP	LAFS	PAF	PF
Relative reduction in sent interests	67.7%	59.4%	61.3%	59.5%	5.7%	57.8%
Relative reduction in sent data	40.7%	56.4%	50.4%	54%	18.6%	37%
Relative reduction in retrieval latency	-14.8%	3.1%	-19%	5.8%	13.3%	24.4%
Relative increase in success rate	0.1%	-1.2%	0.98%	-0.5%	0.80%	4%
Relative increase in remaining energy	53.5%	96.5%	70.1%	84.2%	7.33%	37.5%

Table 7.4: Comparative performance evaluation of DPIF-k=3 against DPIF-k=2 and the forwarding strategies in the 10x10 network with the consumer generating 1 interest/s. Positive percentages indicate improvement while negative percentages indicate degradation in the performance of DPIF relative to the other strategies.

Performance metrics	DPIF-k=2	BF	DBF	GOSSIP	LAFS	PAF	PF
Relative reduction in sent interests	-13.8%	62.5%	53%	55.1%	53%	-9.4%	51%
Relative reduction in sent data	-10.3%	34%	51.5%	44.6%	48.5%	9.2%	29.7%
Relative reduction in retrieval latency	7.1%	-7.2%	9.5%	-10.2%	12%	19.1%	29.5%
Relative increase in success rate	0.02%	-0.1%	1.2%	0.9%	0.5%	-0.8%	-4%
Relative increase in remaining energy	-5.4%	45.6%	86.3%	61.2%	74%	1.7%	30.3%

7.4 Conclusions

This chapter has conducted a comprehensive performance evaluation of interest forwarding strategies in NDN over LLNs. We have assessed through extensive simulations the performance of probabilistic forwarding solutions, namely DPIF, GOSSIP, and PF, and well-known existing strategies including BF, DBF, LAFS, and PAF across various performance metrics such as sent interests, sent data, retrieval latency, success rate, and remaining energy.

Our results have demonstrated the superiority of DPIF over the other forwarding solutions, including PF and GOSSIP, in most evaluated aspects. DPIF synergistically incorporates flooding, propagation, forwarding, and duplicate control mechanisms to optimize interest retransmissions and conserve energy resources. As a result, DPIF achieves a lower number of sent interest and data packets, reduced retrieval latency, higher success rates, and lower energy consumption compared to the other competing strategies in most examined static and mobile scenarios.

While PAF was initially proposed for NDN over MANETs, our study is the first to explore its performance properties in the context of NDN over LLNs. Our results have revealed that although PAF utilizes both distance-based propagation control and listening periods to reduce duplicate retransmissions, it exhibits lower performance than DPIF due to the lack of flooding control, which increases the likelihood of interest packets reaching data producers, especially in the presence of high mobility. However, PAF still outperforms GOSSIP, PF, LAFS, DBF, and BF. Moreover, our study has also revealed that although DBF achieves slightly high success rates in most examined cases, it suffers from low remaining energy due to its higher number of sent interest and data packets due to the absence of propagation control.

GOSSIP exhibits similar performance trends as LAFS concerning most performance metrics, as they both permit interest packets to bypass the duplicate control mechanism. On the other hand, PF, which solely employs forwarding control through probabilities, has a lower number of sent interest/data, compared to DBF, GOSSIP, DBF, and BF. Nonetheless, it exhibits the worst retrieval latency and success rate due to the probabilistic drop of interest packets without considering their distance to producers.

Having discussed the aforementioned findings, it is imperative to address specific considerations on the integration of distance-based propagation control in DPIF. Noteworthy is the fact that DPIF necessitates a relatively higher memory allocation for distance tables compared to GOSSIP and PF. However, this memory requirement remains well within a comparable range to that of the existing forwarding solutions including PAF, LAFS, PAF, and R-LF. Furthermore, our extensive performance analysis has elucidated that the effectiveness of DPIF can be influenced by the judicious selection of key parameters, notably the number of flooding hops (k) and the forwarding probability (p). Based on the outcomes of our performance analysis, we advocate setting these parameters at k=2 and p=0.5. This configuration not only ensures DPIF's ability to demonstrate compelling performance attributes across diverse network conditions but also positions it favorably for practical deployment scenarios.

8. Conclusions and Future Directions

Named Data Networking (NDN) implemented over Low-power and Lossy Networks (LLNs) and leveraging IEEE 802.15.4 communication technology [4] is anticipated to offer inherent support for mobility and efficient content delivery for Internet of Things (IoT) applications. This research has undertaken the crucial task of designing interest forwarding strategies for NDN over LLNs, an area of growing importance in light of the expanding IoT landscape. A key highlight of this work is its emphasis on lightweight strategies specifically tailored for resource-constrained LLN devices, characterized by limited computational and communication capabilities and energy constraints.

When NDN is deployed over wireless networks, including LLNs, nodes typically operate with a single interface to communicate with one-hop neighboring nodes. The broadcast nature of the shared wireless medium often leads to a range of issues, collectively known as the broadcast storm problem [23]. These issues encompass redundant packet retransmissions, excessive channel contention, and frequent packet collisions, which can significantly impact network performance. Numerous interest forwarding strategies [24-34] have been proposed to mitigate the degrading effects arising from the broadcast storm problem in NDN deployments over wireless networks.

After providing the necessary background on IoT, LLNs, and NDN in Chapters 2 and 3, respectively, Chapter 4 introduced a novel classification framework for existing interest forwarding strategies developed for NDN over wireless networks, including LLNs. Our classification system categorizes these strategies based on the specific control mechanisms they employ to mitigate the broadcast storm problem. These mechanisms encompass forwarding, flooding, duplicate, and propagation control. Forwarding control determines which network nodes are authorized to retransmit interest packets. Flooding control regulates the spatial extent to which interest packets can disseminate across all directions within the network. Duplicate control identifies and discards duplicate interest packets arriving at an intermediate node. Finally, propagation control ensures that interests advance only within specific network regions hosting potential data producers, contrasting the broader dissemination achieved through flooding control.

Chapter 5 investigated the effectiveness of probabilistic and gossip-based techniques for interest forwarding within the framework of NDN over LLNs. This investigation has been motivated by the fact that although probabilistic schemes have undergone extensive investigation within various wireless networks, such as MANETs [35-38], WSNs [39-42], and VANETs [43-46], due to their simplicity and ease of implementation to address the challenges posed by the broadcast storm problem, their performance metrics have been hardly assessed in the context of NDN over LLNs.

To this end, we described two forwarding strategies, namely Probabilistic Forwarding (PF) and GOSSIP, for efficient data retrieval in LLN environments. The PF strategy leverages a probabilistic mechanism to implement forwarding control. On the other hand, the GOSSIP strategy incorporates flooding, forwarding, and duplicate control to reduce unnecessary interest retransmissions to effectively mitigate the deleterious impact of the broadcast storm problem. Subsequently, our study delves into a comprehensive performance evaluation of these probabilistic techniques. The evaluation aims to identify the optimal settings for crucial parameters governing the operations of their adopted control mechanisms within the context of NDN over LLNs.

Our performance results have revealed that system performance in terms of the success rate and retrieval latency improves as the forwarding probability increases. A similar performance trend for the probabilistic broadcast has been reported when applied in other contexts, such as MANETs [35, 95, 96] with IP configurations. However, existing studies have found that the probability values between $p \approx 0.59$ and $p \approx 0.65$ provide the best performance results and that any further increase in the forwarding probability yields diminishing returns. In contrast, we have noticed that good system performance can be achieved when the probability value is $p > 0.80$, which is considerably higher than that reported in previous studies.

Our performance analysis has also indicated that achieving good performance in the GOSSIP strategy requires a well-balanced configuration of key parameters: the number of flooding hops (k), forwarding probability (p), and duplicate threshold (m). Starting with the number of flooding hops (k), based on the performance results presented in Chapter 5, it is recommended to set a low value, e.g. $k=2$ or 3. This choice strikes a balance between data propagation and network efficiency, ensuring fast data retrieval without causing excessive flooding. Moving on to the forwarding probability (p), a recommended range falls between 0.6 and 0.70. This range allows for selective forwarding of interest packets while preserving energy efficiency. Such values of p contribute to maintaining stable packet transmission rates, facilitating efficient data delivery without overwhelming the network with superfluous traffic. Lastly, regarding the duplicate threshold (m), setting m to 2 is recommended as this configuration minimizes unnecessary packet transmissions and optimizes energy consumption.

Our review of existing forwarding strategies has uncovered a common shortcoming among existing strategies, such as DBF [30] and LAFS [31] —they often incorporate duplicate control but lack propagation control, leading to excessive and unnecessary interest retransmissions. Conversely, the limited number of strategies integrating propagation control, such as PAF [28] and LFBL [34], exhibit unsatisfactory performance in the presence of producer mobility, primarily due to the absence of flooding control. Based on these observations, Chapter 6 suggested a new forwarding strategy, referred to as Distance-based Probabilistic Interest Forwarding (or DPIF for short), for NDN over LLNs. DPIF optimizes interest forwarding by seamlessly integrating flooding, forwarding, propagation, and duplicate control mechanisms. A key strength of DPIF lies in its adept management of producer mobility, achieved through judicious flooding control. Additionally, DPIF leverages estimated distance to producers, probabilities, and listening periods to exercise propagation, forwarding, and duplicate control, respectively, thereby enhancing the overall efficiency of the proposed strategy.

Following the description of the DPIF algorithm, Chapter 6 has carried out a comprehensive performance analysis to evaluate the impact of critical parameters governing the operations of the control mechanisms employed by DPIF on the overall system performance. Through extensive experimentation, we have determined that the performance of DPIF is significantly impacted by the careful selection of parameters, particularly the number of flooding hops (k) and the forwarding probability (p). Our findings indicate that configuring k=2 and p=0.5 balances the trade-offs between the number of sent interest/data packets, and thus remaining energy, retrieval latency, and success rates. Additionally, our analysis highlighted the advantage of utilizing distance to data producers as a criterion for dropping interest packets after the expiration of the listening period instead of relying on a threshold for received duplicate packets, as in GOSSIP and DBF. This approach has consistently demonstrated superior performance in reducing unnecessary retransmissions and enhancing overall network efficiency.

Existing research has extensively surveyed diverse forwarding strategies designed for NDN over wireless networks, utilizing IEEE 802.11 and IEEE 802.15.4 communication technologies. However, these surveys have primarily focused on comparing the "conceptual" aspects of these techniques, lacking a comprehensive performance evaluation under realistic conditions involving heavy traffic loads and diverse mobility scenarios. Additionally, our review of the current research literature indicates that the evaluation of most existing forwarding strategies has predominantly involved comparative analyses against DBF and BF. Moreover, existing performance studies have considered either static or mobile scenarios separately, failing to provide comprehensive evaluations encompassing both conditions. This limitation has led to a current knowledge gap regarding the relative performance of these strategies in stationary versus mobile settings. To address this gap, Chapter 7 has presented one of the first comprehensive performance evaluations of major forwarding strategies proposed for NDN over LLNs. Our analysis has spanned diverse network configurations and dynamic operating conditions, aiming to provide novel insights into the performance behavior of these strategies.

Our results have confirmed the superiority of DPIF over the other forwarding solutions, including PF and GOSSIP, in most evaluated aspects. DPIF synergistically incorporates flooding, propagation, forwarding, and duplicate control mechanisms to optimize interest retransmissions and conserve energy resources. As a result, DPIF achieves the lowest number of sent interest and data packets, and thus the lowest energy consumption while achieving acceptable retrieval latency and success rates, compared to the other competing strategies in most examined static and mobile scenarios.

While PAF was initially proposed for NDN over MANETs, our study is the first to explore its performance properties in the context of NDN over LLNs. Our results have revealed that although PAF utilizes both distance-based propagation control and listening periods to reduce duplicate retransmissions, it exhibits lower performance than DPIF due to the lack of flooding control, which increases the likelihood of interest packets reaching data producers, especially in the presence of mobility. However, PAF still outperforms GOSSIP, PF, LAFS, DBF, and BF. Moreover, our study has also revealed that although DBF achieves slightly high success rates in most examined cases, it suffers from low remaining energy due to its higher number of sent interest and data packets due to the absence of propagation control.

GOSSIP exhibits similar performance trends as LAFS concerning most performance metrics, as they both permit interest packets to bypass the duplicate control mechanism. On the other hand, PF, which solely employs forwarding control through probabilities, has a lower number of sent interest/data compared to DBF, GOSSIP, DBF, and BF. Nonetheless, it exhibits the worst retrieval latency and success rate due to the probabilistic drop of interest packets without considering their distance to producers.

Having discussed the aforementioned findings, it is imperative to address specific considerations on integrating distance-based propagation control in DPIF. Noteworthy is the fact that DPIF necessitates a relatively higher memory allocation for distance tables compared to GOSSIP and PF. However, this memory requirement remains well within a comparable range to the existing forwarding solutions, including PAF, LAFS, PAF, and RLF.

8.1 Suggestions for future research

There are several research issues and open problems that require further investigation. These are summarized below.

Dynamic forwarding probabilities: The probabilistic forwarding mechanisms discussed, including PF, GOSSIP, and DPIF, currently utilize fixed probabilities for forwarding control. An interesting line of research to enhance these strategies would explore the feasibility of enabling nodes to dynamically adjust forwarding probabilities based on real-time network conditions. This adaptation should account for variations in link quality, traffic loads, and node mobility, ensuring that forwarding decisions align with the dynamic nature of LLN environments. By developing adaptive forwarding strategies, we can expect a significant improvement in the efficiency of interest forwarding processes, particularly in scenarios characterized by dynamic and unpredictable network conditions.

Unstructured topologies and alternative mobility models: Practical real-world deployments of NDN over LLNs may feature more intricate topologies (e.g., unstructured and random), varied mobility patterns (e.g., random walk), and fluctuating traffic generation patterns (e.g., batch and variable bit generation rates). To attain a comprehensive understanding of DPIF performance across a broader spectrum of LLN scenarios, future research work could extend simulations to incorporate diverse unstructured network topologies. Additionally, exploring alternative mobility models, such as random walk or deterministic mobility patterns, would provide insights into the adaptability of DPIF to varying node movements. Furthermore, investigating fluctuating traffic generation patterns, including batch transmissions and variable bit generation rates, would offer a more realistic representation of data flows in LLN environments. These extensions would contribute significantly to elucidating the performance of interest forwarding strategies in NDN over LLNs under diverse real-world conditions, thus enhancing the practical applicability of our research outcomes.

Lightweight machine learning techniques for interest forwarding in NDN over LLNs: Machine learning techniques have provided a new set of powerful tools to tackle problems in numerous computer fields, including networking [98, 99]. A possible extension of this research would involve integrating machine learning techniques like reinforcement learning and naïve Bayes classifiers into interest forwarding strategies for NDN over LLNs. The aim is to develop lightweight machine-learning models capable of operating within the constraints of LLN devices. These models should adaptively learn and optimize forwarding decisions based on various factors such as network dynamics, data popularity, and device capabilities. Implementing such strategies is expected to enhance the performance and scalability of interest forwarding in LLN environments, effectively addressing the unique characteristics and challenges presented by NDN over LLNs.

Analytical modeling of interest forwarding: While simulation has been extensively used to evaluate the performance of interest forwarding strategies in NDN over LLNs, it often demands significant time and computing resources to run large-scale models. Analytical modeling can present an appealing alternative to simulation primarily due to its lower computing resource requirements. In recent developments, there has been an effort to construct an analytical model for NDN over LLNs [97]. However, this model has primarily focused on estimating the success rate of the BF strategy exclusively. Therefore, an interesting avenue for future research would involve extending the analytical modeling approach to encompass a broader range of forwarding strategies, particularly PF and GOSSIP, in the initial stages. This research would help to acquire a more comprehensive understanding of the performance of interest forwarding strategies in NDN over LLNs in large-scale networks, offering valuable insights into their effectiveness and scalability in diverse network scenarios.

Probabilistic caching techniques in NDN over LLNs: This research has extensively utilized probabilities to develop efficient interest forwarding strategies in NDN over LLNs. An extension of this research would explore the application of probabilities to other critical operational aspects of the NDN paradigm. For instance, a future research study could develop caching strategies that can probabilistically manage cache entries based on factors such as data popularity, device mobility, and network conditions. It is crucial to comprehensively assess the impact of probabilistic caching on various aspects, including data retrieval efficiency, network performance, and resource utilization. This research endeavor can provide valuable insights into optimizing caching mechanisms in LLN environments, ultimately contributing to enhanced system efficiency and scalability.

References

[1] N.A. Gunathilake, A.Y. Al-Dubai, W.J. Buchanan, Internet of Things: Concept, implementation, and challenges. In the Internet of Things and Its Applications, Select Proceedings of ICIA'2020, Springer, pp. 145-155, 2022. Doi: 10.1007/978-981-16-7637-6_14.

[2] L. Atzori, A. Iera, G. Morabito, the internet of things: A survey, Computer Networks, Elsevier, vol. 54, no. 15, pp. 2787-2805, 2010. Doi: 10.1016/j.comnet.2010.05.010.

[3] M. Majid, et. al.: Applications of wireless sensor networks and internet of things frameworks in the industry revolution 4.0: A systematic literature review, Sensors, vol. 22, no. 6, pp. 2087, 2022. Doi: 10.3390/s22062087.

[4] IEEE: Standard for local and metropolitan area networks - Part 15.4: Low-rate wireless personal area networks (LR-WPANs), New York, USA, 2016.

[5] Y. Yang, H. Wang, R. Jiang, X. Guo, J. Cheng, Y. Chen, A review of IoT-enabled mobile healthcare: Technologies, challenges, and future trends, IEEE Internet of Things Journal, vol. 9, no. 12, pp. 9478 – 9502, 2022.

[6] S. H. Shah and I. Yaqoob, A survey: Internet of Things (IoT) technologies, applications and challenges, Proc. 2016 IEEE Conf. on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 2016, pp. 381-385, doi: 10.1109/SEGE.2016.7589556.

[7] J. Kurose, K. Ross, Computer Networking: A Top-Down Approach, 7th Edition, Pearson; April 26, 2016. ISBN: 978-0133594140.

[8] B. Ghaleb, et. al., A survey of limitations and enhancements of the IPv6 routing protocol for low-power and lossy networks: A focus on core operations, IEEE Communications Surveys & Tutorials, vol. 21, pp. 1607-1635, 2018.

[9] S. Balaji, K. Nathani, R. Santhakumar, IoT Technology, Applications and challenges: A contemporary survey, Wireless Personel Communications, vol. 108, pp. 363–388, 2019. Doi: 10.1007/s11277-019-06407-w.

[10] B.B. Gupta M. Quamara, An overview of Internet of Things (IoT): Architectural aspects, challenges, and protocols Concurrency and Computation: Practice & Experience, 1-2, 42018. Doi: 0.1002/cpe.4946.

[11] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, A survey of information-centric networking, IEEE Communications Magazine, vol. 50, no. 7, pp. 26-36, 2012. Doi: 10.1109/MCOM.2012.6231276.

[12] K. Xue, D.S.L Wei, D.S Bruschi, I. Chih-Lin, The quest for information-centric networking. IEEE Communications Magazine, vol. 57, no. 6, 2019.

[13] L. Chinmayee, M. Hurali, A.P. Patil, Application areas of information-centric networking: State-of-the-art and challenges. IEEE Access, vol. 10, pp.122431-122446, 2022.

[14] N. Boubakr, et. al.: A survey of Internet of Things communication using ICN: A use case perspective, Computer Communications vol. 142, pp. 95-123, 2019.

[15] L. Wang, A. Afanasyev, R. Kuntz, R. Vuyyuru, R. Wakikawa, L. Zhang, Rapid traffic information dissemination using named data, Proc. 1st ACM Workshop Emerging Name-Oriented Mobile Networking Design - Architecture, Algorithms, and Applications. 12, ACM, NY, USA, pp. 7–12, 2012.

[16] V. Jacobson, D.K. Smetters, J.D. Thornton, M.F. Plass, N.H. Briggs, R.L. Braynard, Networking named content. Proc. 5th Int. Conf. Emerging Networking Experiments & Technologies, ACM, pp. 1–12, 2009.

[17] D. Saxena, V. Raychoudhury, N. Suri, C. Becker, J. Cao, Named Data Networking: A survey. Computer Science Review, vol. 19, pp. 15-55, 2016.

[18] M. Amadeo, C. Campolo, A. Iera, A. Molinaro, Named data networking for IoT: An architectural perspective, 2014 European Conference on Networks and Communications (EuCNC), Bologna, Italy, 2014, pp. 1-5, doi: 10.1109/EuCNC.2014.6882665.

[19] M. A. Hail, IoT-NDN: An IoT Architecture via Named Data Networking (NDN), Proc. 2019 IEEE International Conference on Industry 4.0, Artificial Intelligence, and Communications Technology (IAICT), Bali, Indonesia, pp. 74-80, 2019. Doi: 10.1109/ICIAICT.2019.8784859.

[20] M. Amadeo, C. Campolo and A. Molinaro, Internet of Things via Named Data Networking: The support of push traffic, Proc. 2014 International Conference and Workshop on the Network of the Future (NOF), Paris, France, pp. 1-5, 2014. Doi: 10.1109/NOF.2014.7119766.

[21] V. Jacobson et al., Networking named content, Proc. 5th Int. Conf. Emerging Networking Experiments & Technologies (CoNEXT), Rome, Italy, pp. 1–1, 2009. Doi: 10.1145/1658939.1658941.

[22] IEEE: IEEE Std. 802.11-2020 IEEE Standard for Information Technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications (2020).

[23] Y.C Tseng, S.Y Ni, Y.S. Chen, J.P. Sheu, The broadcast storm problem in a mobile ad hoc network, Wireless Networks, vol. 8, no. 2, pp. 153–167, 202.

[24] A. Tariq, R.A. Rehman, B.S. Kim, Forwarding strategies on NDN-based wireless networks: A survey, IEEE Communications Surveys & Tutorials, vol. 22, no. 1, pp. 68 – 95, 2020.

[25] A. Djama, B. Djamaa, M.R. Senouci, Information-centric networking solutions for the Internet of things: a systematic mapping review, Computer Communications vol. 159, pp. 37–59, 2020.

[26] F. Baccelli, C. Mehlis, O. Hahm, T.C. Schmidt, M. Wählisch, Information-centric networking in the IoT: Experiments with NDN in the wild, Proc. 1st ACM Conference on Information-Centric Networking (ICN'2014), pp. 77–86, NY, USA, 2014.

[27] Y.T. Yu, R.B. Dilmaghani, S. Calo, S., M.Y. Sanadidi, M. Gerla, Interest propagation in named data MANETs, Proc. 2013 Int. Conf. Computing, Networking and Communications (ICNC), pp. 1118–1122, 2013. Doi: 10.1109/ICCNC.2013.6504249.

[28] M. Amadeo, C. Campolo, A. Molinaro, Forwarding strategies in named data wireless ad hoc networks: design and evaluation, Journal of Network and Computer Applications, vol. 50, pp. 148–158, 2015.

[29] N. Askar, et. al, Forwarding strategies for named data networking based IoT: Requirements, taxonomy, and open research challenges, IEEE Access vol. 11, pp. 78363-78383, 2023. Doi: 10.1109/ACCESS.2023.3276713.

[30] M. Amadeo, A. Molinaro, G. Ruggeri, E-CHANET: routing forwarding and transport in Information-Centric multi-hop wireless networks, Computer Communications, vol. 36, no. 7, pp. 792–803, 2013.

[31] A. Djama, B. Djamaa, M.R. Senouci, LAFS: a learning-based adaptive forwarding strategy for NDN-based IoT network, Annals of Telecommunications, Springer, vol. 77, pp. 311–330, 2022. Doi: 10.1007/s12243-021-00850-2.

[32] Z. Gao, H. Zhang, B. Zhang, Energy efficient interest forwarding in NDN-based wireless sensor networks, Mobile Information Systems, pp. 1-15, 2016. Doi: 10.1155/2016/3127029.

[33] A. Abane, M. Daoui, S. Bouzefrane, P. Mühlethaler, A lightweight forwarding strategy for Named Data Networking in low-end IoT, Journal of Network and Computer Applications (JNCA), vol. 48, pp. 102445, 2019.

[34] M. Michael, P. Vasileios, Z. Lixia, Listen first, broadcast later: Topology-agnostic forwarding under high dynamics, Proc. Annual Conference of International Technology Alliance in Network and Information Science, 2010.

[35] D. G. Reina, S. L. Toral, P. Johnson, and F. Barrero, A survey on probabilistic broadcast schemes for wireless ad hoc networks, Ad Hoc Networks, vol. 25, pp. 263–292, 2015. Doi: 10.1016/j.adhoc.2014.10.001.

[36] F. Palmieri, A wave propagation-based adaptive probabilistic broadcast containment strategy for reactive MANET routing protocols, Pervasive and Mobile Computing, Vol. 40, 2017, pp. 628-638. Doi: 10.1016/j.pmcj.2017.06.024.

[37] H.T. Adarbah, S. Ahmad, Channel-adaptive probabilistic broadcast in route discovery mechanism of MANETs, Journal of Communications Software and Systems, vol. 15, no. 1, pp. 34-43, 2019. Doi: 10.24138/jcomss.v15i1.538.

[38] F. Forero, N.M. Peña, L. Nelson, S. da Fonseca, Latency reduction in probabilistic broadcast protocols for ad hoc networks, IEEE Wireless Communications Letters, vol.8, no.4, pp.1268-1271, 2019.

[39] C. Sengul, M.J. Miller, I. Gupta, Adaptive probability-based broadcast forwarding in energy-saving sensor networks, ACM Transactions on Sensor Networks, vol. 4, no. 6, pp. 1–32, 2008. Doi: 10.1145/1340771.1340772.

[40] I. Chatzigiannakis, T. Dimitriou, S. Nikoletseas, P. Spirakis, A probabilistic algorithm for efficient and robust data propagation in wireless sensor networks, Ad Hoc Networks, vol. 4, no. 5, pp. 621-635, 2006. Doi: 10.1016/j.adhoc.2005.06.006.

[41] D. Chang, K. Cho, N. Cho, T.T. Kwon, Y. Choi, A probabilistic and opportunistic flooding algorithm in wireless sensor networks, Computer Communications, vol. 35, no. 4, pp. 500-506, 2012. Doi: 10.1016/j.comcom.2011.11.016

[42] R. Arroyo-Valles, R. Alaiz-Rodriguez, A. Guerrero-Curieses and J. Cid-Sueiro, Q-Probabilistic Routing in Wireless Sensor Networks, Proc. 2007 3rd International Conference on Intelligent Sensors, Sensor Networks and Information, Melbourne, VIC, Australia, pp. 1-6, 2007. Doi: 10.1109/ISSNIP.2007.4496810.

[43] A. Srivastava, A. Prakash, R. Tripathi, Fuzzy-based beaconless probabilistic broadcasting for information dissemination in urban VANET, Ad Hoc Networks, vol. 108, no. 1, 2020, pp. 102285. Doi: 10.1016/j.adhoc.2020.102285

[44] L. Liu, C. Chen, T. Qiu, M. Zhang, S. Li, B. Zhou, Data dissemination scheme based on clustering and probabilistic broadcasting in VANETs, Vehicular Communications, vol. 13, pp. 78-88, 2018. Doi: 10.1016/j.vehcom.2018.05.002.

[45] T. Saeed, Y. Mylonas, A. Pitsillides, V. Papadopoulou, M. Lestas, Modeling probabilistic flooding in VANETs for optimal rebroadcast probabilities, IEEE Transactions on Intelligent Transportation Systems, vol. 20, no. 2, pp. 556-570, Feb. 2019. Doi: 10.1109/TITS.2018.2828413.

[46] X. Zeng, M. Yu, D. Wang, A new probabilistic multi-hop broadcast protocol for vehicular networks, IEEE Transactions on Vehicular Technology, vol. 67, no. 12, pp. 12165-12176, 2018. doi: 10.1109/TVT.2018.2872998.

[47] Z. Haas, J. Halpern, L. Li, Gossip-based ad hoc routing, Proc. IEEE INFOCOM, New York, USA, 2002.

[48] I.S. Lysiuk, Z. J. Haas, Controlled gossiping in ad hoc networks, Proc. 2010 IEEE Wireless Communication and Networking Conference, Sydney, NSW, Australia, 2010, pp. 1-6. Doi: 10.1109/WCNC.2010.5506346

[49] T.-C. Huang, S. -C. Chen, L. Tang, Energy-aware gossip routing for mobile ad hoc networks, Proc. 2011 IEEE International Conference on High Performance Computing and Communications, Banff, AB, Canada, 2011, pp. 955-959, doi: 10.1109/HPCC.2011.139.

[50] Z.J. Haas, J.Y. Halpern, L. Li, Gossip-based ad hoc routing, IEEE/ACM Transactions on Networking, vol. 14, no. 3, pp. 479- 491, 2006.

[51] A.S. Ould Khaoua, B. Fella, A. Boukra, Gossip-based interest forwarding in NDN over MANETs, Proc. Int. Conf. Advances in Electronics, Control & Communication Systems (ICAECCS'2023),Blida, Algeria, pp. 1-6, 2023/ Doi: 10.1109/ICAECCS56710.2023.10104735.

[52] CISCO, Cisco Annual Internet Report (2018–2023), white paper, 2023

[53] A. Klubnikin. Internet of things: How much does it cost to build iot solution?, URL https://r-stylelab.com/company/blog/iot/internet-of-things-how-much-does-it-cost-to-build-iot-solution.

[54] L. Su.Vailshery, Number of Internet of Things (IoT) connected devices worldwide from 2019 to 2023, with forecasts from 2022 to 2030. Statista, July 202. https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/

[55] B.K. Tripathy, J. Anuradha, Internet of Things (IoT): Technologies, applications, challenges and solutions, CRC Press, Taylor & Francis Publisher, October 2017, ISBN: 9781315269849.

[56] A. Verma, P. Verma, Y. Farhaoui, Z. Lv, Editors, Emerging Real-World Applications of Internet of Things, CRC Press, 2022, ISBN: 1032302607,9781032302607.

[57] S. N. Mohanty, J.M. Chatterjee, S. Satpathy, Editors, Internet of Things and Its Applications, Springer, Year: 2021, ISBN: 3030775275/9783030775278.

[58] S. Satapathy, D. Mishra, A. R. Vargas, Innovation in agriculture with IoT and AI, Springer, 2022, ISBN: 9783030888275/9783030888282.

[59] M. Amadeo et. al., Information-centric networking for the internet of things: challenges and opportunities. IEEE Network, vol. 30, no. 2, pp. 92–100, 2016. Doi:10.1109/MNET.2016.7437030.

[60] A. Klubnikin, IoT Agriculture: How to Build Smart Green-house?, b. URL https://r-stylelab.com/company/blog/iot/iot-agriculture-how-to-build-smart-greenhouse.

[61] R. Alexander, A. Brandt, J.P. Vasseur, J. Hui, K. Pister, P. Thubert, P Levis, R. Kelsey, T. Winter, RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. RFC 6550, March 2012. URL: https://rfc-editor.org/rfc/rfc6550.txt.

[62] ZigBee Alliance, What is ZigBee?, URL http://www.zigbee.org/what-is-zigbee/.

[63] IEEE. IEEE standard for information technology– local and metropolitan area networks–specific

requirements– part 15.1a: Wireless medium access control (mac) and physical layer (phy) specifications for wireless personal area networks (wpan), IEEE Std 802.15.1-2005 (Revision of IEEE Std 802.15.1-2002), pp. 1–700, June 2005. Doi: 10.1109/IEEESTD.2005.96290.

[64] Bluetooth Special Interest Group. 2019. Bluetooth Core Specification Version 5.1. Technical Report. URL: https: //www.bluetooth.com/specifications/bluetooth-core-specification.

[65] LoRa Alliance. LoRaWAN R1.0. Open Standard Released for the IoT; LoRa Alliance: Fremont, CA, USA, 2015.

[66] J. Haxhibeqiri, E. De Poorter, I. Moerman, J. Hoebeke, A survey of LoRaWAN for IoT: From technology to application, Sensors, vol. 18, no. 11, 2018. Doi: 10.3390/s18113995.

[67] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert, J. P. Koskinen, Overview of narrowband IoT in LTE Rel-13, Proc. IEEE Conf. Stand. Communication Networks (CSCN), Berlin, Germany, pp. 1–7, 2016.

[68] J. Xu , J. Yao, L. Wang, Z. Ming, K. Wu, L. Chen, Narrowband internet of things: Evolutions, technologies, and open issues, IEEE Internet of Things, Vol. 5, No. 3, 2018.

[69] M.A. Majeed, T.D. Rupasinghe, Internet of things (IoT) embedded future supply chains for Industry 4.0: An assessment from an ERP-based fashion apparel and footwear industry, Int. J. Supply Chain. Management, vol. 6, pp. 25–40, 2017.

[70] S. Kumar, P. Tiwari, M. Zymbler, M. Internet of Things is a revolutionary approach for future technology enhancement: A review. J. Big Data, vol. 6, pp. 1–21, 2019.

[71] B. Baccala. Data-oriented networking, Internet draft, IETF, August 2002.

[72] T. Koponen et al., A data-oriented (and beyond) network architecture, Proc. SIGCOMM ’07, Kyoto, Japan, Aug. 27–31, 2007.

[73] Scalable and Adaptive Internet Solutions (SAIL). URL: http://www.sail-project.eu/.

[74] B. Ahlgren et al., Second NetInf architecture description, 4WARD EU FP7 Project, Deliverable D-6.2 v2.0, Apr. 2010, FP7-ICT-2007-1-216041- 4WARD / D-6.2, http://www.4ward-project.eu/.

[75] L. Zhang et al. Named Data Networking (NDN) Project, October 2010. http://named-data.net/ndn-proj.pdf.

[76] L. Zhang et al., Named data networking, ACM SIGCOMM Computer Communication Review, vol. 44, no. 3, pp. 66–73, 2014. Doi: https://doi.org/10.1145/2656877.2656887.

[77] NDN Team. NDN packet format specification. URL: http://named-data.net/doc/NDN-packet-spec/current/.

[78] NDN Project Team. NDN technical memo: Naming conventions, Technical Report NDN-0022, NDN, July 2014. URL: https://named-data.net/wp-content/uploads/2014/08/ndn-tr-22-ndn-memo-naming-conventions.pdf.

[79] NDN Website. NDN protocol design principles. URL: https://named-data.net/project/ndn-design-principles/.

[80] W. Shang, A. Afanasyev, L. Zhang. The design and implementation of the NDN protocol stack for RIOT-OS, Proc. 2016 IEEE Globecom Workshops, pp. 1–6, 2016. Doi: 10.1109/GLOCOMW.2016.7849061.

[81] J. Shi, B. Zhang. NDNLP: A link protocol for NDN, Technical Report NDN-0006, NDN, July 2012.

[82] A. Abane, A realistic named data networking architecture for the Internet of things: Networking and internet architecture, Doctoral Dissertation, University of Mouloud Mammeri, Tizi-Ouzou, Algeria, 2020.

[83] Aboud, A., Touati, H., Hnich, B.: Efficient forwarding strategy in an NDN-based internet of things. Cluster Computing, vol. 22, no. 3, pp. 805–818, 2019.

[84] M. Chowdhury, J.A. Khan, L. Wang, Leveraging content connectivity and location awareness for adaptive forwarding in NDN-based mobile ad hoc networks, Proc. 7th ACM Conference on Information-Centric Networking (ICN'2020), pp. 59–69, Sept. 2020. Doi: https://doi.org/10.1145/3405656.3418713.

[85] M. Kuai, X. Hong, Location-based deferred broadcast for ad-hoc named data networking, Future Internet, vol. 11, no. 6, pp. 139. 2019. Doi: 10.3390/fi11060139.

[86] Y. Lu, B. Zhou, L.-C. Tung, M. Gerla, A. Ramesh, L. Nagaraja, Energy efficient content retrieval in mobile cloud, Proc. 2nd ACM SIGCOMM workshop on Mobile cloud computing, pp. 21–26, ACM, 2013. Doi: 10.1145/2491266.2491271.

[87] F. Angius, M. Gerla, G. Pau, BlooGo: Bloom filter-based gossip algorithm for wireless NDN. Proc. 1st ACM workshop on Emerging Name-Oriented Mobile Networking Design- Architecture, Algorithms, and Applications, ACM, pp. 25–30, 2012.

[87] N. Dehaghani, R. Sadeghi, S.M.F. Imani, REF: A novel forwarding strategy in wireless NDN,'' Wireless Personal Communication, vol. 117, no. 2, pp. 1025–1042, 2021. Doi: 10.1007/s11277-020-07909-8.

[88] M. Amadeo, C. Campolo, A. Molinaro, A novel hybrid forwarding strategy for content delivery in wireless information-centric networks. Computer Communication, vol. 109, pp. 104–116, 2017.

[89] X. Guo, Y. Chen, L. Cao, D. Zhang, Y. Jiang, A receiver-forwarding decision scheme based on Bayesian for NDN-VANET, China Communications, vol. 17, no. 8, pp. 106-120, Aug. 2020, doi: 10.23919/JCC.2020.08.009

[90] ndnSIM Simulator, 08, 2020. https://ndnsim.net/current/. Accessed on 19 December 2023.

[91] D.B. Johnson, D.A. Maltz, Dynamic source routing in ad hoc wireless networks, Mobile Computing, The Kluwer International Series in Engineering and Computer Science, vol. 353, pp. 153–181, 1996.

[92] The Network Simulator. https://www.nsnam.org/ accessed on 24 October 2023.

[93] A.S. Ould Khaoua, A. Boukra, F. Bey, Probabilistic forwarding in named data networks for internet of things, In: Chikhi, S., Diaz-Descalzo, G., Chaoui A., Saidouni, D.E., Kholladi, M.K. (Eds.) Modeling and Implementation of Complex Systems. MISC 2022. Lecture Notes in Networks and Systems, 593, Springer, 2023. Doi: 10.1007/978-3-031-18516-8_2.

[94] A.S. Ould Khaoua, A. Boukra, F. Bey, Performance evaluation of probabilistic interest forwarding in NDN over LLNs. Proc. 3rd International Conference on Human-Centric Smart Environments for Health and Well-being (IHSH' 2022), IEEE, pp. 37-42, 2022.

[95] M. Bani Yassein, S.F. Nimer, S.F., A.Y. Al-Dubai, A new dynamic counter-based broadcasting scheme for Mobile Ad hoc Networks, Simulation Modelling Practice and Theory, vol. 19, no. 1, pp. 553-563, 2011.

[96] S.O. Al-Humoud, L.M. Mackenzie, J. Abdulai, Neighbourhood-aware counter-based broadcast scheme for wireless ad hoc networks. Proc. IEEE Globecom Workshops, IEEE, New Orleans, LA, USA, pp. 1-6, 2008. Doi: 10.1109/GLOCOMW.2008.ECP.45.

[97] A.S. Ould Khaoua, A. Boukra, A., B. Fella, On estimating the interest satisfaction ratio in IEEE 802.15.4-based named-data networks. Annals of Telecommunications, vol. 79, no. 1-2, pp. 111-130, 2024. Doi: 10.1007/s12243-023-00983-6.

[98] R. Boutaba, et. al., A comprehensive survey on machine learning for networking: evolution, applications and research opportunities, Journal of Internet Services & Applications, vol. 9, no. 16, pp. 99, 2018,. Doi: 10.1186/s13174-018-0087-2.

[99] R. Mayasari and N. R. Syambas, Machine learning on named data network: a survey routing and forwarding strategy, Proc. 14th International Conference on Telecommunication Systems, Services, and Applications, Bandung, Indonesia, 2020, pp. 1-5. Doi: 10.1109/TSSA51342.2020.9310909.

Publications during this research

Scholarly Journal:

A.S. Ould Khaoua, A. Boukra, F. Bey, On efficient interest forwarding in named data networks over IEEE 802.15.4: A comprehensive performance evaluation, Cluster Computing, Springer, 2024. Doi: 10.1007/s10586-024-04398-3.

International Conferences:

A.S. Ould Khaoua, F. Bey, A. Boukra, Listen first broadcast later for interest forwarding in named data networks over LLNs, Proc. 2023 International Conference on Networking and Advanced Systems (ICNAS'2023), IEEE, Algiers, Algeria, pp. 1-6, , 2023. Doi: 10.1109/ICNAS59892.2023.10330460.

A.S. Ould Khaoua, F. Bey, A. Boukra, Gossip-based interest forwarding in NDN over MANETs, Proc. 2023 International Conference on Advances in Electronics, Control and Communication Systems (ICAECCS'2023), IEEE, BLIDA, Algeria, , pp. 1-6, 2023. Doi: 10.1109/ICAECCS56710.2023.10104735.

A.S. Ould Khaoua, A. Boukra, F. Bey, Performance evaluation of probabilistic interest forwarding in NDN over LLNs, Proc. 2022 3rd International Conference on Human-Centric Smart Environments for Health and Well-being (IHSH'2022), IEEE, Lévis, QC, Canada, pp. 37-42, 2022. Doi: 10.1109/IHSH57076.2022.10092161.

A.S. Ould Khaoua, A. Boukra, F. Bey, Probabilistic forwarding in named data networks for internet of things. In: Chikhi, S., Diaz-Descalzo, G., Amine, A., Chaoui, A., Saidouni, D.E., Kholladi, M.K. (eds) Modelling and Implementation of Complex Systems (MISC2022), Lecture Notes in Networks and Systems, vol 593, 2023, Springer, Cham, Doi: 10.1007/978-3-031-18516-8_2.