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An Energy-Aware Multi-Packet Forwarding and Mobility-Resilient Caching Model for IoT-Enabled Named Data Ad Hoc Networks

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Abstract- Named Data Networking (NDN) is attractive for IoT-enabled ad hoc networks because content can be retrieved by name and satisfied by intermediate caches. However, wireless broadcast forwarding can create redundant Interest and Data transmissions, while one-Interest-one-Data retrieval, cache/PIT processing overhead, limited battery capacity, and node mobility increase retrieval delay and energy consumption. This paper presents an energy-aware multi-packet forwarding and mobility-resilient caching model for IoT-enabled NDN ad hoc networks. The proposed model combines a bounded one-Interest-multiple-packets mechanism with a per-packet status map, hash-based Content Store and Pending Interest Table management, delayed Interest merging, residual-energy admission, and mobility-triggered re-requesting. We compared our work with Blind Forwarding (BF) and E-DRAFT, which introduced accumulative Interest retrieval and a B+Tree-based Content Store for NDN-based wireless multimedia sensor networks. Results under static and mobile conditions show that the proposed model reduces Interest and Data forwarding, lowers content retrieval time, improves lookup efficiency, and extends node lifetime compared with BF.

Keywords- Named Data Networking; Internet of Things; Ad Hoc Networks; Energy-Aware Forwarding; Mobility-Aware Caching

1. Introduction

The traditional Internet follows a host-centric communication model in which data are exchanged between network endpoints identified by addresses. This model establishes communication with a particular network location before the requested information can be retrieved. Many current Internet applications, however, are centered on accessing content rather than communicating with a specific host. In such cases, the primary requirement is to obtain the requested content, regardless of the network location from which it is delivered. Applications such as video streaming, social networking, cloud storage, mobile services, and Internet of Things (IoT)-based sensing generate and consume massive amounts of named content across heterogeneous and mobile environments. The conventional TCP/IP architecture has a number of limitations in these situations, such as location dependence, inadequate support for in-network caching, ineffective content retrieval, scalability problems, costs associated with mobility management, and duplicated data transfer.

By replacing content-based naming for host-based addressing, NDN has been proposed as a potential future Internet architecture to get over these limitations. An NDN consumer provides an Interest packet with the name of the desired content instead of sending packets to a destination IP address. The necessary data packet may be returned by the producer or any intermediary node that has a cached matching copy. Because of this, NDN is a perfect match for networks with limited resources, mobile communication, and content delivery. NDN architecture is based on two types of packets, Interest and Data, and three main data structures on routers, the Content Store (CS), Pending Interest Table (PIT) and

Forwarding Information Base (FIB). The CS briefly caches the incoming Data packets, the PIT records the unsatisfied Interests and the FIB forwards the Interests towards possible sources of content [1]. The NDN project description also states that if several Interests for the same data are received from downstream interfaces, only the first Interest is transmitted upstream, and returning Data is forwarded to all requesting interfaces and cached in the CS.

These features make NDN suitable for wireless ad hoc networks such as Mobile Ad Hoc Networks (MANETs), Vehicular Ad Hoc Networks (VANETs), IoT networks and wireless sensor networks. In these networks the nodes connect without a fixed infrastructure and each node might be a consumer, a producer or a relay. NDN allows intermediary nodes to cache and return content regardless of the location of the original producer, and therefore it can reduce delay of retrieval and enhance availability of content. Recent research further highlight the advantages of NDN-based wireless ad hoc networks such as in-network caching, mobility support, scalability, security, and location-independent data access [1-3]. However, these benefits are not obtained automatically. The broadcast nature of wireless communications, frequent mobility of nodes, limited battery capacity, and unpredictable connectivity create various performance difficulties.

Packet flooding is a major problem in NDN-based ad hoc networks. In a wired NDN network, Interest forwarding normally takes relatively stable channels using FIB-based forwarding, whereas Data packets come back along the reverse path built in PIT. On the other hand, wireless ad hoc communication is broadcast-based. A node flooding an Interest packet might reach numerous neighbors. Excessive Interest flooding, redundant Data transmission, packet collision, and unnecessary energy consumption may occur if these neighbors re-broadcast the same Interest packets or return duplicate Data packets. The problem is multiplied when the same content is broken down into many Data packets and the user has to send an Interest for each packet. We highlight that the traditional "one Interest for one Data packet" behavior is a main reason for inefficiency of round-trip time and redundant forwarding in wireless NDN setups.

Another major restriction is the operation efficiency of CS and PIT. Each arriving Interest requires a lookup in the CS to verify whether the requested Data is locally available. If no matching Data is available, the node checks the PIT to see if the same Interest is pending. Similarly when a Data packet comes, the PIT must be checked to identify the requested downstream interfaces and the Data may also be inserted into the CS for future use. Therefore, lookup, insertion, update and deletion operations in CS and PIT directly influence the forwarding delay and node processing overhead.

Mobility adds a further aspect to the complexity of ad hoc communication based on NDN. In a mobile ad hoc network, the positions of consumers, producers and intermediate nodes may shift throughout the retrieval of content. A consumer may send an Interest from one location and then relocate before all Data packets are received. Similarly, a producer or intermediate node may move out of transmission range during the time a request is partially satisfied. In this instance, the consumer might receive just some packets of a multi-packet content object, while other packets might be lost, or delayed until the relevant PIT entries expire. The significance of the problem is also stressed in recent NDN mobility literature, where the dynamic movement of producers and consumers impacts on the handoff latency, the efficiency of packet delivery and the performance of data retrieval [4, 5]. We takes into consideration a consumer mobility scenarios when a consumer shifts positions before all data packets arrive, resulting in an incomplete or only partially completed request.

Another important issue with wireless ad hoc networks is energy usage. Nodes in sensor-based systems, MANETs, and IoT networks frequently run on constrained battery power. If every node continuously participates in Interest forwarding, Data forwarding, caching, and retransmission, low-energy nodes may deplete their batteries quickly. This can reduce node lifetime and may also damage network connectivity. Existing energy-aware NDN forwarding schemes, such as OEFS, consider residual energy during forwarding decisions [6]. Other recent works have also continued to investigate smart and energy-aware forwarding for NDN-based environments, confirming that energy-efficient forwarding remains a relevant research direction [7,8]. However, many energy-aware approaches either focus on single-packet forwarding or require additional control messages to exchange energy information, which may itself increase overhead.

Several existing schemes have attempted to address forwarding, caching, energy, or mobility issues in NDN-based wireless networks. Blind Forwarding (BF) uses simple broadcast forwarding but may generate excessive redundant packets. LOMCF improves forwarding and caching in NDN-based MANETs by using location-aware multipath forwarding and caching decisions [3]. REF reduces redundant PIT entries in wireless NDN, but its forwarding process is mainly based on single-packet requests [9]. OEFS considers the residual energy of a node before forwarding an Interest and is intended to reduce unnecessary energy consumption in wireless NDN ad hoc networks [6]. Other studies address different parts of the same problem. Multipath Interest forwarding is considered in [10], cache replacement and cache organization are studied in [11,12], and mobility recovery is addressed in [13,14]. More recent studies also report that cache placement, limited storage, mobility, and resource constraints remain relevant issues in wireless NDN and IoT environments [15,16]. The studies reviewed above generally address forwarding, caching, mobility, or energy management as separate functions. Most of them also retain the conventional one-Interest-one-Data exchange, which requires a separate request for each Data packet.

A closely related paper for our work is E-DRAFT [17]. E-DRAFT uses an accumulative Interest mechanism for NDN-based wireless multimedia sensor networks and employs an array-based B+Tree Content Store to improve Data retrieval and control packet flooding. The present work follows the same general direction of reducing unnecessary packet exchange, but considers a different forwarding problem. It maintains the status of individual Data packets inside an Interest and combines this information with hash-based CS/PIT access, residual-energy checking, delayed Interest processing, and consumer mobility recovery. These functions are intended for IoT-enabled ad hoc networks where packet retrieval may be affected by both node energy and movement. Based on these observations, we develop an energy-aware multi-packet forwarding and cache-assisted mobility model for NDN-based ad hoc networks. A consumer does not generate a separate Interest for every Data packet. Instead, one Interest carries a packet-status map that records the packets that are still required and those that have already been received. An intermediate node checks this map before forwarding the Interest. It can satisfy available packets from its local CS, update the corresponding PIT information, and forward the request only for packets that remain unresolved.

The forwarding process also considers the operating condition of the intermediate node. CS and PIT entries are maintained through hash-based structures to support frequent lookup and update operations. The node checks a freshly received Interest's remaining energy against a predetermined threshold before transmitting it. After an Interest is approved, it is stored for a brief period of time so that requests coming in from various routes can be pooled before being forwarded onward. When a continuous retrieval is still pending, mobility is taken into consideration. An additional Interest is produced for the packets that are still unresolved rather than for the entire content if the consumer travels farther than the set distance threshold. The main contributions of this paper are summarized as follows:

- We introduce a multi-packet forwarding mechanism for NDN-based ad hoc networks in which a single Interest can represent the retrieval state of several Data packets rather than requesting each packet independently.
- We add packet-level retrieval state into Interest processing through a status map that distinguishes received packets from unresolved packets. Intermediate nodes use this state during PIT updates, cache lookup, and subsequent Interest forwarding.
- We organize CS and PIT entries using hash-based structures to support frequent content lookup and packet-status updates with average-case $O(1)$ access.
- We add residual energy into the Interest-forwarding decision. A node whose available energy is below the configured threshold does not accept a new Interest-forwarding task.
- A short delayed-processing interval is used to combine overlapping Interests received through different paths before they are forwarded further.
- Consumer mobility is handled by monitoring displacement from the request location. When the configured threshold is exceeded, only the packets that remain missing are requested again.
- The model is implemented and evaluated in ndnSIM under ad hoc network conditions using packet-transmission overhead, content retrieval time, CS/PIT lookup, node lifetime, and mobility-related measurements.

The remainder of this paper is organized as follows. Section 2 discusses previous work on NDN forwarding, caching, energy-aware communication, mobility, and CS/PIT organization. Section 3 defines the network model and formulates the problem. Section 4 describes the proposed forwarding model and its packet-processing procedure. Section 5 presents the simulation configuration and evaluation metrics. The results are discussed in Section 6, followed by limitations and future work in Section 7. Section 8 concludes the paper.

2. Related Work

Existing work on wireless NDN has mainly considered forwarding control, caching, energy consumption, node mobility, and the organization of CS and PIT. The papers most closely related to the present work are discussed below.

2.1. Forwarding Strategies in NDN-Based Wireless Networks

Wireless NDN normally relies on broadcast communication. As a result, an Interest transmitted by one node can be received by several neighboring nodes. This is useful for discovering content, but repeated forwarding of the same Interest can also increase duplicate packets and channel contention. Early work on Interest propagation in named-data MANETs examined this behavior and the cost of broadcast-based forwarding [2]. Blind Forwarding (BF) follows the same basic broadcast principle and therefore provides reachability at the expense of additional packet transmissions. Several forwarding schemes attempt to control this overhead in different ways. LOMCF uses node location and multipath caching information when forwarding content in NDN-based MANETs [3]. REMIF delays Interest processing so that redundant requests received through multiple paths can be reduced [10]. REF focuses on duplicate PIT entries and suppresses redundant Interest processing [9]. Tariq et al. [1] review these and other wireless NDN forwarding approaches and discuss the trade-offs among packet redundancy, delay, mobility, and energy use. SEF later combines forwarding decisions with node energy and contextual information in a constrained NDN environment [7]. These approaches improve different parts of wireless forwarding, but their request handling is still largely based on individual Data packets. The present work instead keeps the retrieval status of several packets in the same Interest.

2.2. Caching Strategies in NDN-Based Ad Hoc Networks

The CS allows an intermediate NDN node to satisfy an Interest without contacting the original producer. This property is useful in ad hoc networks because node movement or temporary link failure may make the producer unavailable during content retrieval. Cache organization and replacement therefore affect both retrieval delay and the amount of traffic forwarded through the network. Existing schemes use different criteria for managing cached Data. Least Fresh First removes cached content according to freshness [11], whereas CaDaCa groups Data according to its category before making caching decisions [12]. Qazi et al. [18] focus on the internal organization of the CS and use a two-tier tree structure to reduce Data access time in NDN-based wireless sensor networks. Recent studies continue to identify storage capacity, cache placement, replacement decisions, and changing network topology as practical limitations in wireless NDN and IoT networks [15,16]. In the present model, caching is tied directly to multi-packet forwarding. An intermediate node checks its CS against the packet-status map and returns only the requested packets that are locally available.

2.3. Energy-Aware Forwarding in NDN

Energy consumption is an important constraint in wireless NDN because an ad hoc node may perform several roles during the same communication session. It can generate Interests, relay packets for other nodes, cache Data, and later act as a content source. Repeated transmission and reception therefore consume energy even when a node is not the original consumer or producer. Several energy-aware forwarding schemes have been proposed. Gao et al. [19] forwarded Interests through nodes satisfying an energy threshold, while OEFS considers residual energy and delayed forwarding to reduce energy consumption in NDN-based wireless ad hoc networks [6]. Aboud et al. [20] proposed an energy-efficient forwarding strategy for NDN-based IoT using producer discovery and path selection. Recent studies also show that packet size, caching policy, forwarding strategy, and node energy significantly affect NDN-IoT performance [8]. However, many energy-aware schemes treat energy as a separate forwarding criterion and may require additional control overhead. The proposed model integrates energy checking directly into the forwarding pipeline, where a node accepts new Interests only if its residual energy is above a threshold, while still allowing already pending Data forwarding to complete.

2.4. Mobility Support in NDN-Based Networks

Mobility is a natural motivation for NDN because data is requested by name rather than by host address. In NDN, a consumer requests content by name rather than by the location of a specific producer. An intermediate node can also satisfy the Interest if the requested Data is available in its local cache. Mobility, however, can still interrupt an ongoing retrieval in an ad hoc network. A consumer may change its position after transmitting an Interest and before all requested Data packets have returned. This may result in PIT expiry, route interruption, or further Interest transmissions, and it may only partially satisfy the request. In [14], the authors proposed a mobility link service for customer movement while AFIRM handles mobility through adaptive forwarding and link recovery [13]. Other papers look at the impact of producer mobility on packet delivery, signaling overhead, and handoff time [4,5]. Following a mobility incident, these methods mostly deal with path recovery, handoff management, or forwarding adaption. The retrieval status of several data packets within the same interest is not explicitly maintained by them. In the proposed model, mobility recovery is applied when a consumer changes position before a multi-packet request has been completed. The request location is stored when the Interest is generated. If the consumer moves beyond the configured distance threshold, the current packet-status map is examined to identify the packets that are still unresolved. A new Interest is then generated for those packets only and the Data packets already received by the consumer remain marked as satisfied which are then excluded from the new request.

2.5. Data Structure Optimization for CS and PIT

CS and PIT access is performed repeatedly during NDN packet processing. When an Interest arrives, the node first searches its CS for matching Data. If the requested Data is not available locally, the PIT is examined for an existing entry before the Interest is forwarded further. Data processing also requires a PIT lookup to identify the pending request and may subsequently require insertion of the received packet into the CS. A received Data packet requires a corresponding PIT search and may subsequently be inserted into the CS. These operations are performed repeatedly during forwarding, so their access cost contributes to the processing delay of an intermediate node. Several studies have considered more efficient structures for NDN packet storage and retrieval. Qazi et al. [18], for example, use a two-tier tree architecture to reduce CS access time in NDN-based wireless sensor networks. High-performance forwarding platforms such as NDN-DPDK address the same issue from a packet-processing perspective. These designs are useful for efficient lookup, but they are not intended specifically for the packet-status operations required by multi-packet Interests in wireless ad hoc networks. In the proposed model, CS and PIT entries are maintained using hash-based structures. The content name is used as the lookup key, while the associated Data or pending-request information is stored as the corresponding value. Under normal hash-table operation, lookup and update have average-case complexity $O(1)$. This is useful when an intermediate node repeatedly checks cached packets and updates the status of received or missing Data. The actual access time still depends on the hash function, collision handling, and the number of stored entries.

3. System Model and Problem Formulation

This section presents the system model and problem formulation for the proposed model. The model considers an NDN-based wireless ad hoc network in which nodes may act as consumers, producers, or relay nodes. The main objective is to reduce redundant Interest/Data transmissions, improve CS/PIT access, preserve node energy, and support consumer mobility.

3.1. Network and NDN Model

Consider a wireless ad hoc NDN network consisting of N mobile nodes:

$$\mathcal{N} = \{n_1, n_2, \ldots, n_N\}. \tag{1}$$

Each node may operate as a consumer, producer, or relay. Nodes communicate through wireless broadcast. A node n_j is considered a neighbor of node n_i at time t if

$$d(n_i(t), n_j(t)) \leq R_i, \tag{2}$$

where R_i is the transmission range of node n_i. The neighbor set is defined as

$$\mathcal{H}_i(t) = \{n_j \in \mathcal{N} \mid d(n_i(t), n_j(t)) \leq R_i, i \neq j\}. \tag{3}$$

In NDN, a consumer sends an Interest packet for named content, and the corresponding Data packet can be returned by the original producer or by an intermediate node having the content in its CS. In wireless ad hoc environments, however, the same Interest may be received and forwarded by multiple neighbors, causing redundant Interest/Data transmissions, collisions, and energy waste.

3.2. Content and Multi-Packet Interest Model

Let C_m denote a named content object divided into K_m Data packets:

$$C_m = \{D_{m,1}, D_{m,2}, \ldots, D_{m,K_m}\}. \tag{4}$$

Each Data packet is represented as

$$D_{m,k} = \{name_m, packetNo_k, totalPackets_m, signature, payload\}. \tag{5}$$

In conventional NDN, retrieving K_m packets may require approximately K_m separate Interests:

$$I_{conv}(C_m) \approx K_m. \tag{6}$$

The proposed model modifies this behavior by allowing one Interest to request multiple packets using a packet-status map:

$$I_m = \{name_m, nonce, M_m, B, t_c, t_r, L_c\}, \tag{7}$$

where M_m is the packet-status map, B is the maximum number of packets retrieved per Interest, t_c is the creation time, t_r is the forwarding time, and L_c is the consumer location at request generation. The packet-status map is defined as

$$M_m = \{(1, s_1), (2, s_2), \ldots, (K_m, s_{K_m})\}, \tag{8}$$

where

$$s_k = \begin{cases} 0, & \text{if } D_{m,k} \text{ is still required,} \\ 1, & \text{if } D_{m,k} \text{ has been received or satisfied.} \end{cases} \tag{9}$$

Thus, the number of consumer-generated Interests can be reduced to

$$I_{Eco}(C_m) \approx \left\lceil \frac{K_m}{B} \right\rceil, \tag{10}$$

and the potential Interest reduction is

$$\Delta I = K_m - \left\lceil \frac{K_m}{B} \right\rceil. \tag{11}$$

3.3. CS, PIT, and Redundancy Model

Each node n_i maintains a local CS and PIT. In the proposed model, both structures are managed using hash-based indexing:

$$CS_i[name_m] = \{D_{m,1}, D_{m,2}, \ldots, D_{m,q}\}, \tag{12}$$

$$PIT_i[name_m] = \{nonce, M_m, F_{in}, t_c, t_r, L_c\}, \tag{13}$$

where F_{in} denotes incoming faces or neighboring nodes. Hash-based access provides average-case lookup complexity:

$$T_{lookup}^{hash} = O(1). \tag{14}$$

The total number of Interest transmissions is modeled as

$$N_I = \sum_{i=1}^{N} x_i, \tag{15}$$

where $x_i = 1$ if node n_i forwards an Interest. Similarly, Data transmissions are represented as

$$N_D = \sum_{k=1}^{K_m} \sum_{i=1}^{N} y_{i,k}, \tag{16}$$

where $y_{i,k} = 1$ if node n_i forwards packet $D_{m,k}$. The proposed model reduces N_I and N_D by suppressing requests for packets already marked as received in M_m.

3.4. Energy and Mobility Model

Each node n_i has residual energy $E_i(t)$. A node accepts a new Interest only if its energy is above the threshold E_{th}:

$$A_i(t) = \begin{cases} 1, & E_i(t) \geq E_{th}, \\ 0, & E_i(t) < E_{th}. \end{cases} \tag{17}$$

The total consumed energy is expressed as

$$E_C = \sum_{i=1}^{N} \left(E_i^{tx} + E_i^{rx} + E_i^{proc} \right), \tag{18}$$

where E_i^{tx}, E_i^{rx}, and E_i^{proc} denote transmission, reception, and processing energy, respectively. For mobility, the position of node n_i at time t is

$$L_i(t) = (x_i(t), y_i(t)). \tag{19}$$

If a consumer generates an Interest at time t_0, its displacement at time t is calculated as

$$D_c(t) = \sqrt{(x_c(t) - x_c(t_0))^2 + (y_c(t) - y_c(t_0))^2}. \tag{20}$$

A re-request is triggered when the consumer moves beyond the mobility threshold and some packets are still missing:

$$ReReq_c(t) = \begin{cases} 1, & D_c(t) > D_{th} \text{ and } \exists s_k = 0, \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

3.5. Problem Formulation

The goal of the proposed model is to minimize content retrieval delay, redundant transmissions, energy consumption, and mobility recovery cost. The objective is formulated as

$$\min \mathcal{J} = \alpha T_{CRT} + \beta N_I + \gamma N_D + \delta E_C + \eta R_M, \tag{22}$$

where T_{CRT} is content retrieval time, N_I is the number of Interest transmissions, N_D is the number of Data transmissions, E_C is total energy consumption, and R_M is mobility recovery cost.

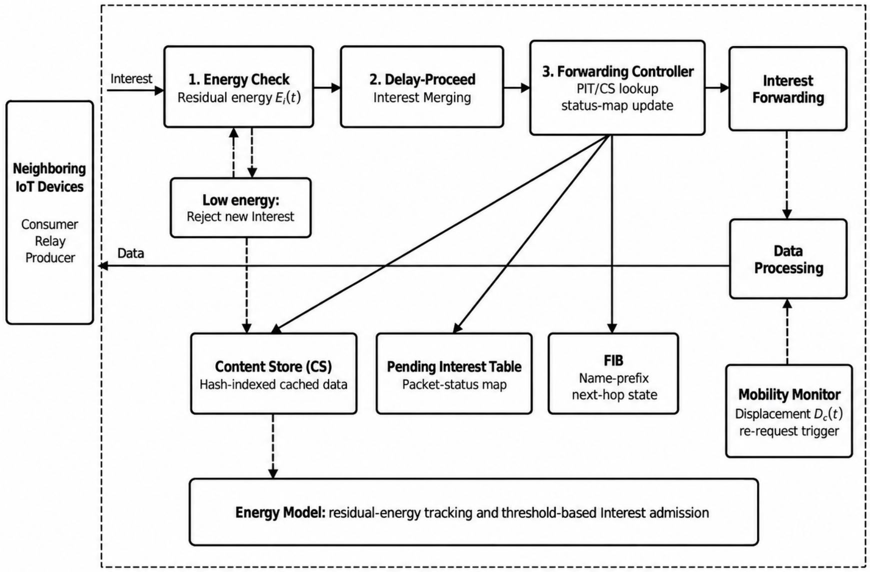

Figure 1: *High-level architecture of the proposed model.*

The optimization is subject to:

$$E_i(t) \geq E_{min}, \quad \forall n_i \in \mathcal{N}_{active}, \tag{23}$$

$$B \leq B_{max}, \tag{24}$$

$$|CS_i| \leq CS_{max}, \tag{25}$$

$$s_k \in \{0, 1\}, \quad \forall k \in \{1, 2, \ldots, K_m\}. \tag{26}$$

Here, E_{min} is the minimum usable energy, B_{max} is the maximum number of packets per Interest, and CS_{max} is the cache capacity of each node.

4. Proposed Energy-Aware Multi-Packet Forwarding Model

The proposed model is designed to improve forwarding, caching, energy efficiency, and consumer mobility support in NDN-based ad hoc networks. The proposed model is built around a different retrieval strategy from conventional NDN forwarding. The proposed model departs from the conventional one-Interest-one-Data exchange by allowing one Interest to describe the retrieval state of several Data packets. A packet-status map is included in each Interest to record the retrieval state of the requested Data packets. A packet-status map accompanies each Interest and records the retrieval state of the requested Data packets. It separates packets that are still waiting from those that the customer has already received. This status is updated in the associated PIT item when an intermediate node gets the Interest. Next, unresolved packets are looked for in the local CS. While only the packets that are still unresolved are kept in the forwarded interest, any matched data can be sent back to the requester.

Scheme Overview

The forwarding procedure combines multi-packet Interest handling, hash-based CS/PIT access, residual-energy checking, delayed Interest merging, and mobility-triggered re-requesting. Retrieval begins when a consumer broadcasts an Interest containing the packet-status map associated with the requested content.

After receiving the Interest, an intermediate node compares its residual energy with the configured threshold. An Interest that satisfies the energy condition is held for a short interval before further processing. During this interval, another Interest with the same content name and nonce may arrive and be merged with the pending request. The PIT state is subsequently updated, and the node searches its CS for packets that are still unresolved.

If an unresolved packet is found in the CS, the corresponding Data packet is returned toward the requesting face or faces. Its status is also updated in the associated PIT entry. Packets that are not available locally remain marked as unresolved. The Interest is forwarded only when at least one requested packet still needs to be retrieved.

Figure 1 summarizes the processing path followed by an incoming Interest. Residual energy is checked before a new forwarding task is accepted. The delayed-processing stage allows overlapping requests to be combined before the forwarding controller accesses the PIT, CS, and FIB. Cached Data may be returned directly when available; otherwise, the unresolved part of the Interest continues toward the next hop. The mobility monitor uses the stored request state and consumer location when retrieval remains incomplete after movement.

Packet Structure and CS/PIT Design

Two packet types are used in the proposed model: Data and Interest. A Data packet is represented as

$$D_{m,k} = \{name_m, packetNo_k, totalPackets_m, signature, payload\}. \tag{27}$$

The Interest packet is extended as

$$I_m = \{name_m, nonce, M_m, B, t_c, t_r, L_c\}, \tag{28}$$

where M_m denotes the packet-status map, B specifies the maximum number of Data packets associated with one Interest, t_c is the creation time, t_r is the forwarding time, and L_c stores the request location.

For content m, the packet-status map is defined as

$$M_m = \{(1, s_1), (2, s_2), \ldots, (K_m, s_{K_m})\}, \tag{29}$$

where the state of packet k is

$$s_k = \begin{cases} 0, & \text{if } D_{m,k} \text{ is still required,} \\ 1, & \text{if } D_{m,k} \text{ has been received or satisfied.} \end{cases} \tag{30}$$

At each node, both the CS and PIT are maintained using hash-based indexing. Their entries are represented as

$$CS_i[name_m] = \{D_{m,1}, D_{m,2}, \ldots, D_{m,q}\}, \tag{31}$$

and

$$PIT_i[name_m] = \{nonce, M_m, F_{in}, t_c, t_r, L_c\}. \tag{32}$$

Under normal hash-table operation, lookup and update require average-case constant time:

$$T_{lookup}^{CS/PIT} = O(1). \tag{33}$$

This complexity is an average-case property and depends on the hash function, load factor, and collision-handling strategy.

Energy-Aware and Delayed Interest Forwarding

Residual energy is examined before a node accepts a new Interest-forwarding task. The admission state is defined as

$$A_i(t) = \begin{cases} 1, & E_i(t) \geq E_{th}, \\ 0, & E_i(t) < E_{th}. \end{cases} \tag{34}$$

When $A_i(t) = 0$, the newly received Interest is not admitted for forwarding. For $A_i(t) = 1$, processing is delayed for an interval Δ. During this period, another Interest carrying the same content name and nonce may be received. If a corresponding PIT entry is already present, the packet-status information is merged according to

$$s_k^{new} = s_k^{in} \vee s_k^{pit}. \tag{35}$$

The logical OR operation preserves a satisfied state whenever either the incoming Interest or the existing PIT entry records packet k as received. Consequently, that packet is removed from the unresolved portion of the request before further forwarding.

Algorithm 1 Interest Processing in the Proposed Model

Require: Interest I_m, node n_i, CS_i, PIT_i
if $E_i(t) < E_{th}$ **then**
    Discard I_m
    return
Hold I_m for the delayed-processing interval
Merge Interests with the same content name and nonce
Create or update the corresponding PIT entry
for each unresolved packet $D_{m,k}$ **do**
    if $D_{m,k} \in CS_i$ and returned packets $< B$ **then**
        Forward $D_{m,k}$ to the requesting face(s)
        Set $s_k \leftarrow 1$
if one or more packets remain unresolved **then**
    Forward the updated Interest

Multi-Packet Forwarding and Data Processing

After the energy and delayed-processing stages, the node searches the PIT using the content name carried by the Interest. If a matching entry exists, its packet-status map is updated with the incoming state. Packets already marked as satisfied require no additional retrieval. The node then searches its local CS for the remaining unresolved packets.

When an unresolved packet is found in the CS, the corresponding Data packet is returned and the related PIT state is updated. Packets unavailable in the local cache remain unresolved and continue with the forwarded Interest. The number of Data packets returned in response to a single Interest is bounded by

$$B_i^{ret} \leq B. \tag{36}$$

Data packets are processed using the pending state stored in the PIT. When $D_{m,k}$ arrives, the node searches for the corresponding PIT entry. If a matching entry is present, the Data packet is inserted into the CS, forwarded toward the recorded requesting face or faces, and marked as received in the packet-status map. The pending entry remains active until all requested packets have been satisfied. It is removed when

$$\sum_{k=1}^{K_m} s_k = K_m. \tag{37}$$

Mobility-Triggered Re-requesting

Consumer movement may interrupt retrieval before all requested Data packets have reached the requester. The consumer location $L_c(t_0)$ is therefore stored when the Interest is generated. At time t, displacement from the original request location is calculated as

$$D_c(t) = \sqrt{(x_c(t) - x_c(t_0))^2 + (y_c(t) - y_c(t_0))^2}. \tag{38}$$

A new Interest is generated only when the consumer moves beyond the configured mobility threshold and at least one packet is still unresolved. This condition is expressed as

$$ReReq_c(t) = \begin{cases} 1, & D_c(t) > D_{th} \text{ and } \exists s_k = 0, \\ 0, & \text{otherwise.} \end{cases} \tag{39}$$

When $ReReq_c(t) = 1$, the current packet-status map is used to construct the new Interest. Data packets received before the movement remain marked as satisfied, whereas only the unresolved packets are included in the re-request. Figure 2 shows the two mobility cases considered in the model. In the first case, the consumer moves before the requested content has been returned and the request remains incomplete. In the second case, some Data packets have already reached the consumer before the movement occurs. The stored packet-status map distinguishes the received packets from those that still need to be retrieved.

Algorithms 1 and 2 define the two packet-processing paths used by the model. Their interaction is shown in Figure 3. Interest processing includes delayed merging, PIT maintenance, CS lookup, and forwarding of the unresolved part of

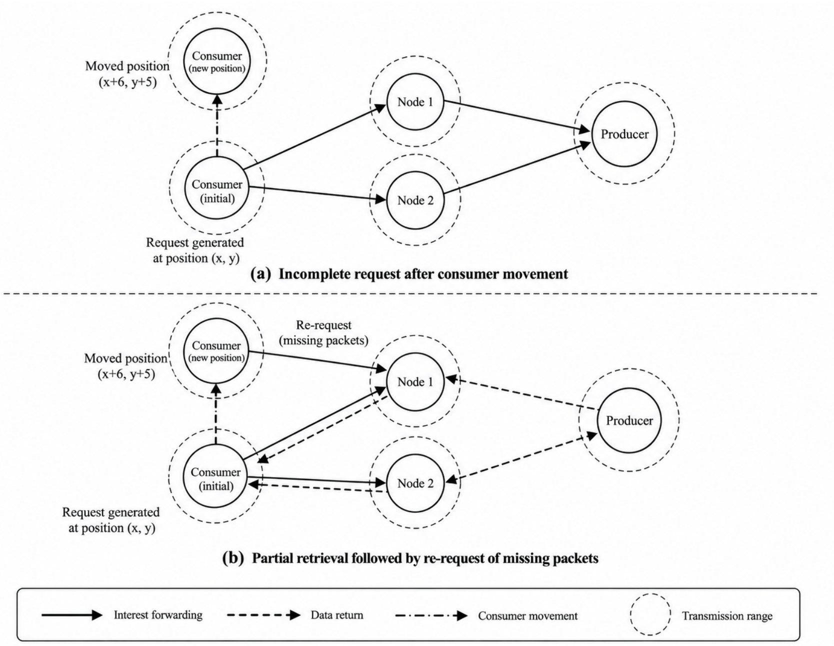

Figure 2: *Consumer mobility cases with incomplete and partially satisfied requests.*

Algorithm 2 Data and Mobility Processing in the Proposed Model

```
Receive Data packet D_{m,k}
Search PIT_i for the corresponding pending Interest
if a matching PIT entry exists then
    Cache D_{m,k} in CS_i
    Forward D_{m,k} to the requesting face(s)
    Set s_k ← 1
    if all requested packets have been received then
        Remove the corresponding PIT entry
Compute the consumer displacement D_c(t)
if D_c(t) > D_{th} and unresolved packets remain then
    Generate a new Interest for the unresolved packets
```

the request. Data processing performs PIT matching, caching, forwarding, and packet-status update. Once all requested packets have been received, the corresponding PIT entry is removed.

4.6. Complexity Analysis

The per-Interest processing cost is determined mainly by CS/PIT access and the update of packet-status entries. The CS and PIT use hash-based indexing so their lookup cost is $O(1)$ on average. For one Interest, status processing is limited to at most B packet entries. The resulting processing complexity is written as:

$$T_{\text{prop}} = O(1) + O(B). \quad (40)$$

The additional $O(B)$ term corresponds to packet-status processing introduced by the multi-packet request. Its purpose is to identify packets that have already been satisfied before another Interest is forwarded. The resulting effect on Interest transmissions, Data transmissions, retrieval time, and node lifetime is evaluated separately in the results section.

5. Experimental Setup

The proposed model is evaluated in ndnSIM over NS-3 using an IoT-enabled NDN ad hoc scenario. The proposed model is compared numerically with Blind Forwarding (BF).

The evaluation considers Interest and Data transmission overhead, content retrieval time (CRT), CS/PIT search time, node lifetime, scaling with consumer-producer pairs, and robustness to increasing node speed.

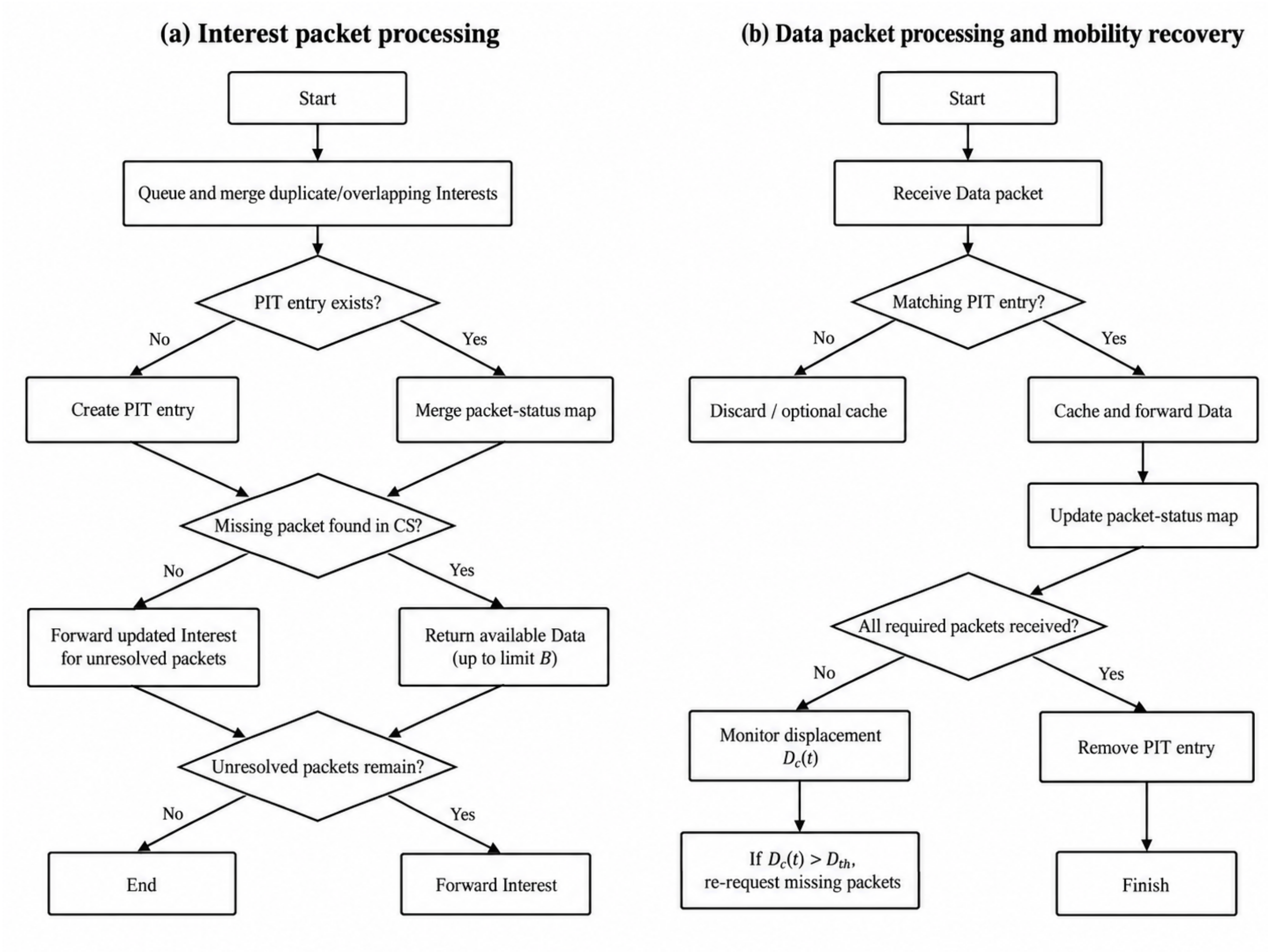

Figure 3: *Interest and Data packet processing flow in the proposed model.*

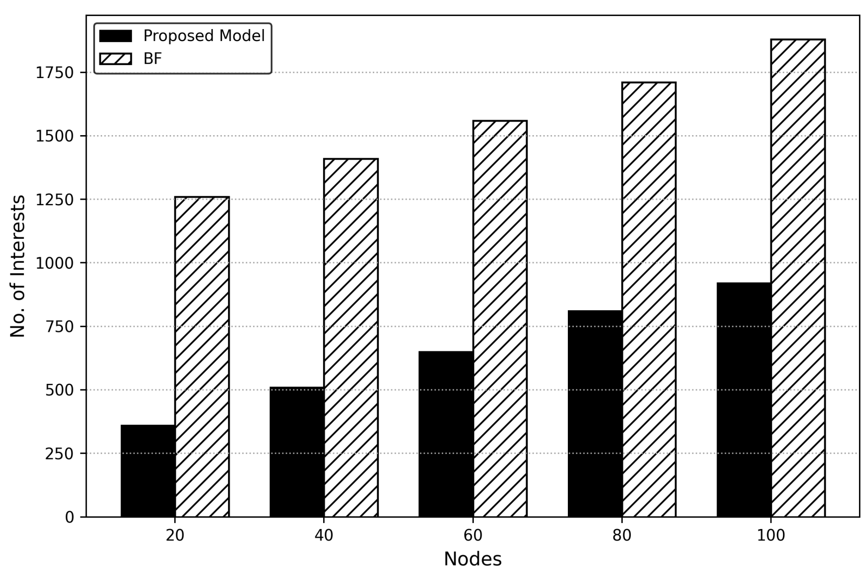

Figure 4: *Interest transmission overhead with increasing number of nodes.*

Table 1: *Simulation parameters.*

Parameter	Value	Unit
Simulation area	1000×1000	m^2
Simulation time	200	s
Number of nodes	50	nodes
Transmission range	250	m
Consumer-producer pairs	1–5	pairs
Content objects	100	names
Packets per content, K_m	20	packets
Data packet size	1024	bytes
Packets per Interest, B	5	packets
CS capacity, $CS_{\max}$	100	packets/node
PIT lifetime	4	s
Interest merge delay	10	ms
Initial node energy	100	J
Energy threshold, E_{th}	20	J
Node speed	0–20	m/s
Mobility threshold, D_{th}	50	m
Independent runs	10	runs
Confidence level	95	%

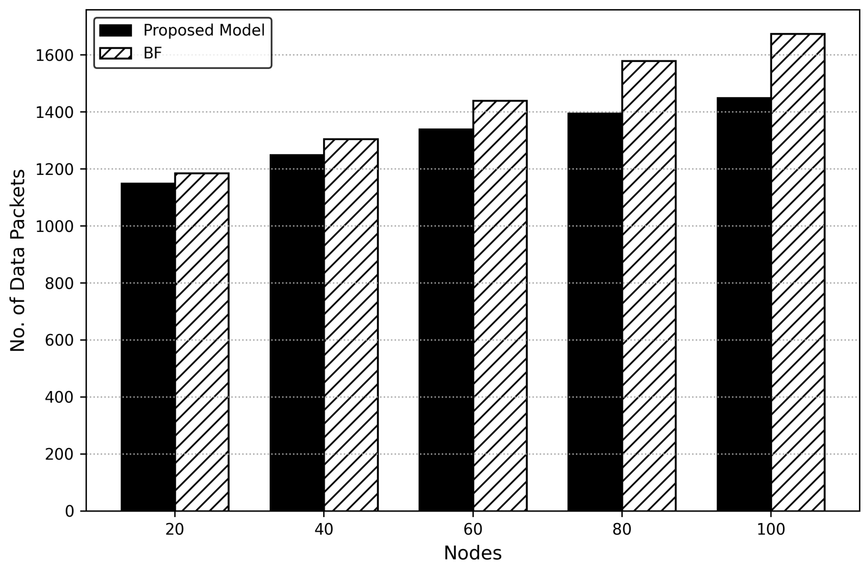

Figure 5: *Data transmission overhead with increasing number of nodes.*

6. Results

The performance evaluation considers Interest transmission overhead, Data transmission overhead, content retrieval time (CRT), CS/PIT search time, node lifetime, consumer-producer pair density, and node mobility. All numerical comparisons in this section use BF as the baseline under the simulation conditions reported in Table 1.

6.1. Interest Transmission Overhead

Interest transmission overhead is evaluated by increasing the number of nodes and recording the total number of forwarded Interest packets. A higher number of Interest transmissions can increase channel contention, PIT occupancy, and the amount of wireless communication performed by intermediate nodes. Figure 4 shows that the proposed model forwards fewer Interest packets than BF at every evaluated network size. This trend is consistent with the multi-packet forwarding procedure. A single Interest can carry the retrieval state of several packets, and packets already marked as received are removed from the unresolved part of the request before further forwarding. As a result, the node does not issue another forwarding request for those packets.

6.2. Data Transmission Overhead

Data transmission overhead is evaluated by counting the Data packets forwarded during content retrieval. In a broadcast-based ad hoc network, the same Data packet may be received by several intermediate nodes and can be forwarded more than once if its retrieval state is not maintained. Figure 5 shows fewer Data transmissions for the proposed model than for BF across the evaluated node counts. When a requested Data packet is received, its status is updated in the corresponding PIT entry. The packet is then treated as satisfied in subsequent processing, while only the packets that remain unresolved continue in the request. The measured Data-transmission trend is consistent with this packet-level update and suppression procedure. The measured trend is consistent with this packet-level suppression mechanism.

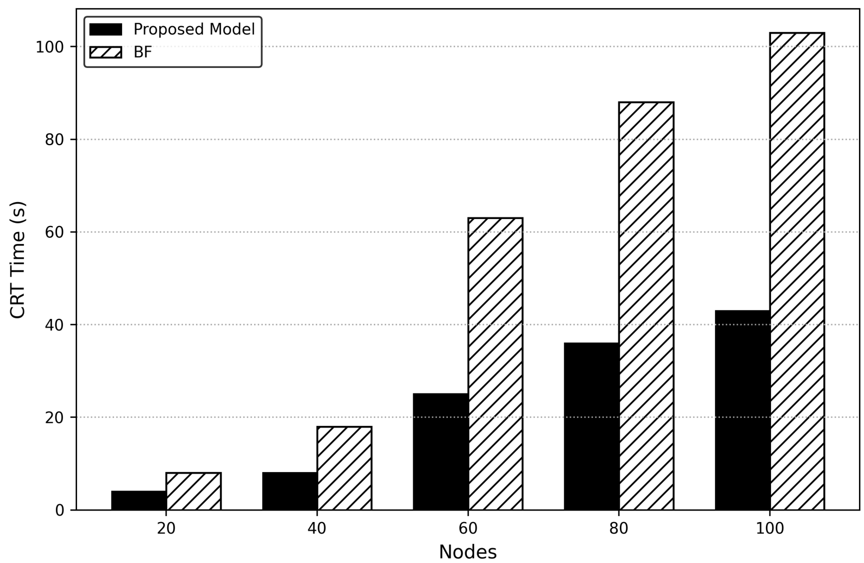

Figure 6: *Content retrieval time with increasing number of nodes.*

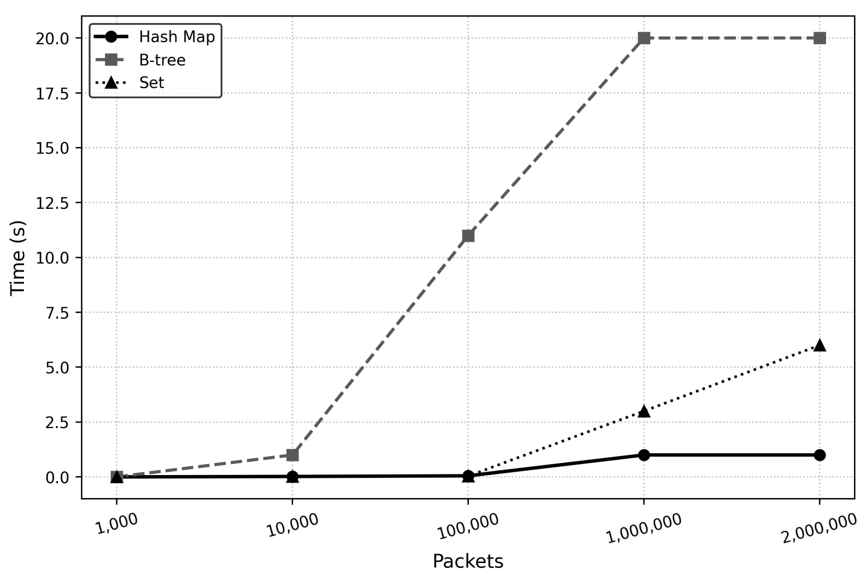

Figure 7: *Search time of the evaluated CS/PIT data structures.*

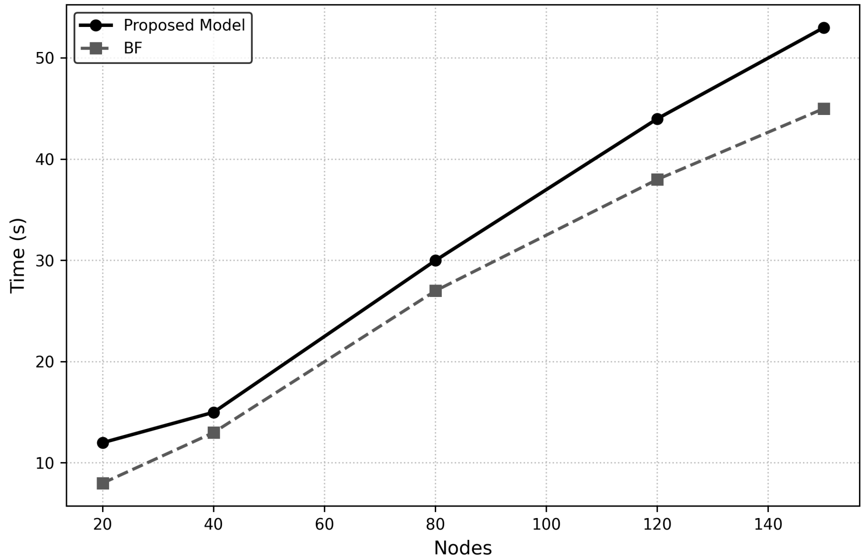

Figure 8: *Node lifetime with increasing network size.*

6.3. Content Retrieval Time

Content retrieval time is measured from the generation of the request until the consumer has received all Data packets belonging to the requested content. The metric therefore captures both forwarding delay and the number of retrieval rounds required to complete the request. Figure 6 shows a lower CRT for the proposed model than for BF at each evaluated network size. In BF, individual requests continue to be disseminated through broadcast forwarding. The proposed model instead allows one Interest to carry the status of several Data packets. Intermediate caches can also satisfy packets that remain unresolved. These two operations reduce the number of separate retrieval cycles required to complete a multi-packet request.

6.4. CS/PIT Search Performance

CS and PIT access is performed repeatedly during Interest and Data processing. The search-time experiment therefore evaluates how the selected data structure behaves as the number of stored packet entries increases. Figure 7 compares the measured search time of the hash-based structure with the B-tree and set implementations. The hash-based implementation maintains the lowest measured search time as the packet set becomes larger. This result is consistent with the use of hash indexing for frequent CS/PIT lookup and packet-status updates. The observation concerns the evaluated implementation and should not be interpreted as a worst-case complexity guarantee. Hash-table performance can still vary with the hash function, load factor, collision handling, and memory allocation.

6.5. Node Lifetime

Node lifetime is used to examine the effect of forwarding activity on the available energy of participating nodes. The experiment records network lifetime while the number of nodes is increased under the same forwarding conditions. The results in Figure 8 show a longer node lifetime for the proposed model than for BF over the evaluated network sizes. This behavior is consistent with two features of the forwarding process. First, the proposed model generates fewer Interest and Data transmissions in the preceding experiments. Second, a node whose residual energy falls below the configured threshold does not accept a new Interest-forwarding task, although Data associated with an already pending request can still be forwarded. The present experiment evaluates their combined effect but it does not isolate the individual contribution of each mechanism.

6.6. Impact of Consumer-Producer Pair Density

The number of simultaneous consumer-producer pairs is varied to examine content retrieval when several communication sessions are active in the same network.

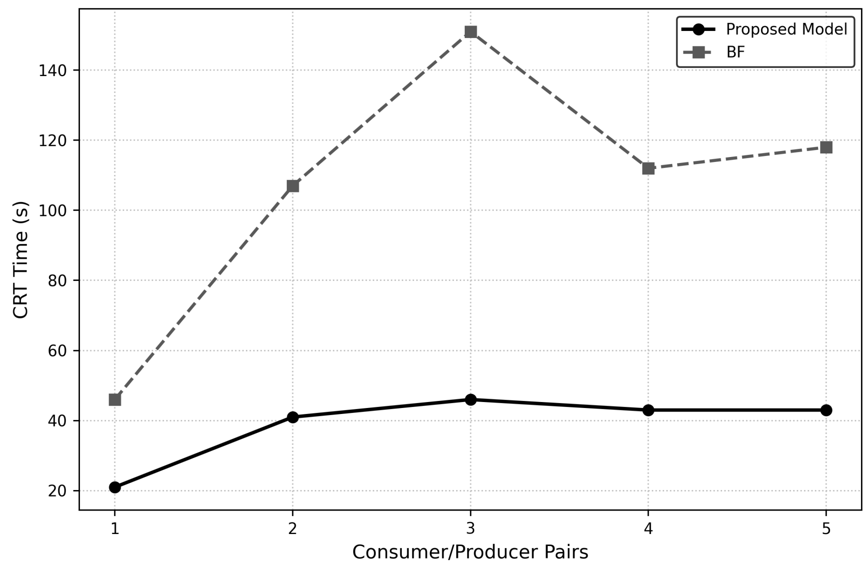

Figure 9: *Content retrieval time with increasing consumer-producer pairs.*

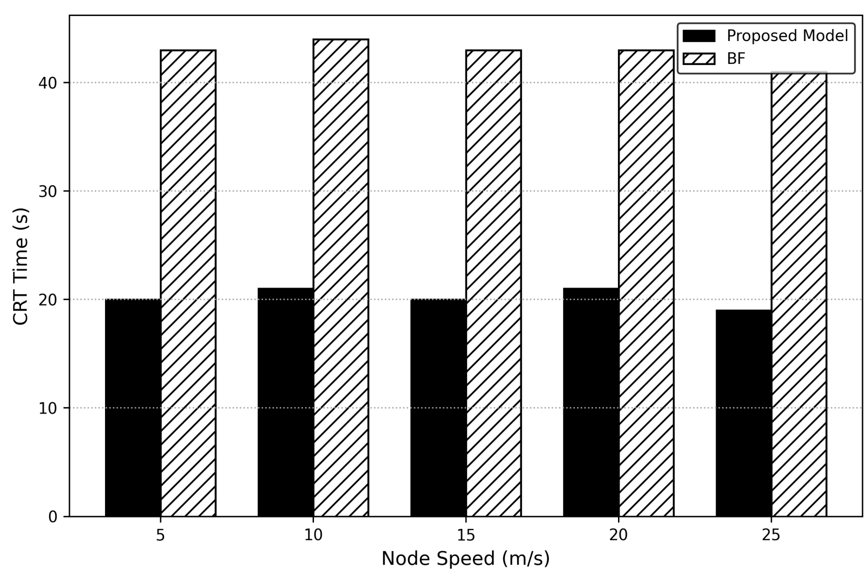

Figure 10: *Content retrieval time under increasing node speed.*

Figure 9 shows a lower CRT for the proposed model than for BF across the evaluated numbers of consumer-producer pairs. In the proposed forwarding process, the packet-status map identifies the part of a request that is still unresolved. An intermediate node checks its CS against these entries and returns any requested packets that are available locally. Packets already received by the consumer remain marked as satisfied and are excluded from subsequent requests. The CRT trend observed in Figure 9 is consistent with this packet-level retrieval procedure when multiple communication sessions are active.

6.7. Impact of Node Speed on Content Retrieval Time

The effect of mobility is evaluated by varying node speed and measuring the time required to complete content retrieval. As nodes move, their neighboring nodes may change while an Interest is still pending. A return path can therefore become unavailable before all requested Data packets reach the consumer. Figure 10 shows that the proposed model has a lower CRT than BF at each evaluated node speed. If consumer movement occurs before the retrieval is complete, the model checks the current packet-status map before generating another Interest. Data packets received before the movement remain marked as satisfied, and the new request contains only the packets that are still unresolved. BF does not maintain the same packet-level retrieval state during mobility. Consequently, it cannot use the received/missing packet information in the mobility recovery procedure employed by the proposed model. The measured CRT difference is consistent with retaining this partial retrieval state when the consumer changes position.

6.8. Comparison with the E-DRAFT Scheme

E-DRAFT [17] is selected as the closest methodological comparator. It is more relevant than a generic location-aware forwarding baseline because both E-DRAFT and the proposed model address multi-request retrieval, flooding, cache organization, and network lifetime. Table 2 summarizes the methodological relationship.

Table 2: *Mechanism-level comparison between E-DRAFT and the proposed model.*

Aspect	E-DRAFT	Proposed model (this work)
Target environment	NDN-based wireless multimedia sensor network	IoT-enabled NDN ad hoc network
Request handling	Accumulative Interest-based content requests	Bounded one-Interest-multiple-packets request with per-packet status map
Flooding control	Timer-based Interest/Data forwarding control	Delay-proceed merging plus packet-status-aware suppression
CS/PIT organization	Array-based B+Tree CS; reported $O(1) + O(\log N)$ architecture	Hash-based CS and PIT; average-case $O(1)$ lookup/update
Energy handling	Lifetime improved indirectly through reduced transmissions	Explicit residual-energy threshold for new Interest admission
Mobility handling	Constant-mobility evaluation; no explicit consumer re-request mechanism	Displacement-triggered re-request for missing packets only
Numerical comparison	Published under a different WMSN simulation configuration	Evaluated under Table 1; direct overlay requires E-DRAFT reimplementation

The comparison shows that the proposed model extends the accumulative-retrieval direction of E-DRAFT with explicit packet-level completion state, energy-aware admission, and consumer-mobility recovery. Importantly, Table 2 is a mechanism-level comparison rather than a claim of numerical superiority across two different simulation configurations. A controlled head-to-head numerical comparison should be added after E-DRAFT is implemented and executed using exactly the same ndnSIM configuration as the proposed model.

7. Limitations

The proposed model has several limitations and they are given below:

- First, the packet-status map adds information to each multi-packet Interest, and its size grows with the number of packet entries represented in the request. This introduces additional packet-processing and communication overhead when content is divided into a large number of packets.
- Second, the current implementation also uses fixed values for the packets-per-Interest limit, residual-energy threshold, and mobility threshold. These values may not remain suitable when network density, link conditions, traffic load, node speed, or available energy changes.
- Third, the mobility procedure, for example, uses consumer displacement as the condition for generating another Interest but does not adjust this threshold according to link quality, PIT expiration, or movement rate.
- Fourth, the energy decision is likewise based on a fixed residual-energy threshold and does not consider the energy state of neighboring nodes.

Conclusion and Future Work

This paper investigated multi-packet content retrieval in IoT-enabled NDN ad hoc networks under energy and mobility constraints. The proposed model combines a packet-status-aware one-Interest-multiple-packets mechanism with hash-based CS/PIT management, delayed Interest merging, residual-energy-based forwarding, and mobility-triggered re-requesting. Under the evaluated scenarios, the proposed model forwarded fewer Interest and Data packets and achieved a lower content retrieval time than BF. It also recorded a longer node lifetime over the evaluated network sizes. For CS/PIT access, the hash-based implementation produced lower measured search times than the compared B-tree and set structures as the number of stored entries increased. The model differs from compared approach architecture by maintaining the retrieval state of individual packets and by incorporating explicit energy-based forwarding and consumer-mobility recovery. These results indicate that packet-level retrieval state can be used to coordinate forwarding, caching, and recovery decisions in resource-constrained NDN ad hoc networks.

Future work will investigate more compact representations of the packet-status map and adaptive selection of the packets-per-Interest value.

Author Declarations

Author Contributions (CRediT): Aditi Nayyer: Conceptualization, Methodology, System Design, Investigation, Visualization, and Writing - Original Draft. Hung Seo Kim: Software, Code implementation, Writing - Original Draft, Writing - Review & Editing. All authors have read and approved the submitted version of the paper.

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References

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

[2] Y. Yu, R. B. Dilmaghani, S. Calo, M. Y. Sanadidi, and M. Gerla, "Interest propagation in named data MANETs," in *Proc. International Conference on Computing, Networking and Communications*, 2013, pp. 1118–1122.

[3] R. A. Rehman and B.-S. Kim, "LOMCF: Forwarding and caching in Named Data Networking based MANETs," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 10, pp. 9350–9364, 2017.

[4] W. M. H. Azamuddin, A. H. M. Aman, H. Sallehuddin, K. Abualsaud, and N. Mansor, "Mathematical models for Named Data Networking producer mobility techniques: A review," *Mathematics*, vol. 12, no. 5, Art. no. 649, 2024, doi: 10.3390/math12050649.

[5] Z. Liu et al., "MsDD: A novel NDN producer mobility support scheme based on multi-satellite data depot," *PLOS ONE*, 2024, doi: 10.1371/journal.pone.0310379.

[6] R. A. Rehman, S. H. Ahmed, and B.-S. Kim, "OEFS: On-demand energy-based forwarding strategy for named data wireless ad hoc networks," *IEEE Access*, vol. 5, pp. 6075–6086, 2017.

[7] N. A. Askar, A. Habbal, H. Hamouda, A. M. Alnajim, and S. Khan, "SEF: A smart and energy-aware forwarding strategy for NDN-based Internet of Healthcare," *Computers, Materials & Continua*, vol. 81, no. 3, pp. 4625–4658, 2024, doi: 10.32604/cmc.2024.058607.

[8] D. Papenfuss, M. T. R. Khan, et al., "Enhancing energy efficiency in IoT-NDN via parameter optimization," *Future Internet*, vol. 16, no. 2, Art. no. 61, 2024.

[9] N. N. Dehaghani, R. Sadeghi, and M. F. Imani, "REF: A novel forwarding strategy in wireless NDN," *Wireless Personal Communications*, vol. 117, no. 3, 2021, doi: 10.1007/s11277-020-07909-8.

[10] R. A. Rehman, T. D. Hieu, H. M. Bae, S. H. Mah, and B.-S. Kim, "Robust and efficient multipath Interest forwarding for NDN-based MANETs," in *Proc. IFIP Wireless and Mobile Networking Conference*, 2016, pp. 187–192.

[11] M. Meddeb, A. Dhraief, A. Belghith, T. Monteil, K. Drira, and H. Mathkour, "Least fresh first cache replacement policy for NDN-based IoT networks," *Pervasive and Mobile Computing*, vol. 52, pp. 60–70, 2019, doi: 10.1016/j.pmcj.2018.12.002.

[12] A. T. Herouala, B. Ziani, C. A. Kerrache, A. E. K. Tahari, N. Lagraa, and S. Mastorakis, "CaDaCa: A new caching strategy in NDN using data categorization," *Multimedia Systems*, 2022, doi: 10.1007/s00530-022-00904-y.

[13] M. Meddeb et al., "AFIRM: Adaptive forwarding based link recovery for mobility support in NDN/IoT networks," *Future Generation Computer Systems*, vol. 87, pp. 351–363, 2018.

[14] J. H. Cha et al., "A mobility link service for NDN consumer mobility," *Wireless Communications and Mobile Computing*, 2018.

[15] A. Khalid, R. A. Rehman, M. Burhan, et al., "Caching strategies in NDN based wireless ad hoc network: A survey," *Computers, Materials & Continua*, vol. 80, no. 1, pp. 1469–1496, 2024, doi: 10.32604/cmc.2024.054448.

[16] A. A. Alahmad, A. H. M. Aman, F. Qamar, and W. Mardini, "Efficient caching strategies in NDN-enabled IoT networks: Strategies, constraints, and future directions," *Sensors*, vol. 25, no. 16, Art. no. 5203, 2025, doi: 10.3390/s25165203.

[17] A. Arsalan, M. Burhan, R. A. Rehman, T. Umer, and B.-S. Kim, "E-DRAFT: An efficient data retrieval and forwarding technique for Named Data Network based wireless multimedia sensor networks," *IEEE Access*, vol. 11, pp. 15315–15328, 2023, doi: 10.1109/ACCESS.2023.3244247.

[18] M. M. Qazi, R. A. Rehman, and B.-S. Kim, "Minimizing content-store data access time using two-tier tree architecture for NDN-based WSNs," in *Proc. IEEE Wireless Communications and Networking Conference Workshops*, 2020, pp. 1–6.

[19] S. Gao, H. Zhang, and B. Zhang, "Energy efficient Interest forwarding in NDN based wireless sensor networks," *Mobile Information Systems*, vol. 2016, 2016.

[20] A. Aboud, H. Touati, and B. Hnich, "Efficient forwarding strategy in a NDN-based Internet of Things," *Cluster Computing*, vol. 22, no. 4, 2019, doi: 10.1007/s10586-018-2859-7.