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Citation: Karim, M. M., Sharif, K., Biswas, S., Latif, Z., Qu, Q. & Li, F. (2024). CIC-SIoT: Clean-Slate Information-Centric Software-Defined Content Discovery and Distribution for Internet-of-Things. *IEEE Internet of Things Journal*, 11(22), pp. 37140-37153. doi: 10.1109/jiot.2024.3441814

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Link to published version: <https://doi.org/10.1109/jiot.2024.3441814>

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CIC-SIoT: Clean-Slate Information-Centric Software-Defined Content Discovery and Distribution for Internet-of-Things

Md Monjurul Karim, Kashif Sharif, Sujit Biswas, Zohaib Latif, Qiang Qu, and Fan Li

Abstract—The rapid expansion of the Internet of Things (IoT) introduces critical challenges in scalability, mobility, and security, particularly in large-scale deployments. While Information-Centric Networking (ICN) addresses these by enhancing content mobility, multipath support, and edge-embedded caching with inherent security features, it faces limitations in handling large heterogeneous environments due to its in-network caching and content-based forwarding strategies. Software-Defined Networking (SDN) complements ICN by employing a centralized controller to intelligently orchestrate content caching and forwarding, yet struggles with the efficient allocation and acquisition of content across expansive IoT systems. In response to these challenges, we propose CIC-SIoT, a novel Information-Centric Software-Defined Networking (IC-SDN) solution, designed to optimize the ICN-IoT framework. Our solution incorporates specialized algorithms for controllers, consumers, producers, and ICN nodes. These algorithms improve content forwarding decisions by moving beyond the traditional reliance on the Forwarding Information Base (FIB) and instead utilizing the Pending Interest Table (PIT) to efficiently manage and distribute content. Validated through ndnSIM and MATLAB simulations, CIC-SIoT achieves substantial performance enhancements, including an 80% increase in throughput, a 34% reduction in latency, and a 25% savings in bandwidth. Additionally, it reduces packet loss by 67% and communication overhead by 66%, compared to existing solutions. These results underscore the framework’s ability to significantly improve the efficiency and scalability of content distribution in IoT environments, highlighting its robustness and adaptability in addressing the complex dynamics of modern networked systems.

Index Terms—Software-Defined Networking, Information-Centric Networking, Internet-of-Things, TLV, Pending Interest Table.

I. INTRODUCTION

Emerging technologies such as the Internet of Things (IoT), Content Delivery Network (CDN), big data, and blockchain

This work was supported in part by the Beijing Natural Science Foundation under Grant IS23056. The work of Fan Li is partially supported by the NSFC (No. 62372045). (*Corresponding author: K. Sharif.*)

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Digital Object Identifier 10.1109/XXX.2023.XXXXXXX

are heavily dependent on fifth-generation (5G) cellular networks [1]. This dependence necessitates the rapid distribution of vast amounts of content to multiple locations within milliseconds. Consequently, network operators face significant challenges in balancing available bandwidth, Quality-of-Service (QoS), and Quality-of-Experience (QoE) [2]. For instance, ensuring scalability, mobility, and security in distributed IoT networks becomes a complex task for operators, especially when these factors need to be addressed concurrently and on the same scale [3]. Software-Defined Networking (SDN) has emerged as a promising solution to address some of the aforementioned challenges, offering programmability and virtualization of data plane entities such as routers, switches, and WiFi access points. This is achieved by separating the data plane from the control logic [4]. However, while SDN presents numerous advantages, it is not without its drawbacks. Specifically, due to the stateless behavior of data plane devices and the single point of failure inherent in SDN controllers, it faces challenges related to scalability, resiliency, awareness, abstraction, and automation tradeoffs [5].

Information-Centric Networking (ICN) emerges as a new paradigm of communication model to tackle some of the issues faced by SDN in a heterogeneous IoT network by offering content mobility with access-agnostic multipath support, edge-embedded caching capabilities, and built-in security [6]. ICN adopts a communication principle that relies on data requests and retrieval through multiple nodes, routers, or forwarding instances capable of stateful forwarding. ICN routers are most influential in offering in-network caching functionalities and dictating named-based stateful forwarding among multiple consumers and producers. Content-Centric Networking (CCN) [7] and Named Data Networking (NDN) [8] are two of the real-world ICN implementations extensively used in academia and industry. Despite these advancements, the performance of ICN routers suffers significantly in large-scale networks [9]–[11]. For example, Drescher et al. [9] highlight the direct impact of PIT occupancy on network congestion by suggesting that the scalability of ICN routers is inherently tied to their ability to manage the growing volume of interest packets in large-scale deployments. On the other hand, Liu et al. [10] propose enhancements to content router architectures, focusing on distributed caching and modular design to better accommodate the scaling demands of ICN routers. Moreover, the increasing number of cache hits in ICN routers introduces overflow in FIB and PIT due to their limited table size, impacting the ICN routers’ request and retrieval efficiency [11]. In

this context, an alternative approach is necessary to overcome the inherent limitations of ICN, particularly the scalability challenges and the complexity of managing dynamic network conditions in large-scale IoT environments. The impact of PIT on scalability is also highlighted in [12]–[15].

The Information-Centric Software-Defined Networking (IC-SDN) model addresses some of the above-mentioned challenges by embedding an SDN control logic within ICN-capable routers. This integration facilitates stateful routing and enhances the efficiency of flow-based data forwarding and content caching [16]. Content distribution in IC-SDN is managed by a centralized controller that facilitates named-based intelligent content discovery and distribution within a large-scale IoT network [17]. The IC-SDN controller uses a content management module to extract content names from requested packets and to insert new entries into the ICN routers. Unlike traditional ICN/NDN scenarios, ICN routers in IC-SDN act as stateless devices, simply forwarding content requests from various consumers to the controller. This integration streamlines control over the content flow but also introduces challenges, particularly within the IoT paradigm. These challenges include managing the substantial volume of data from IoT devices, ensuring their real-time processing and responsiveness, and securing the data during transmission. The diverse range of IoT devices and their communication protocols requires IC-SDN to adopt adaptable and flexible routing strategies. Moreover, the stateless routers in IC-SDN do not make autonomous caching decisions or optimize data flow based on local conditions, leading to potential inefficiencies in network resource utilization. Such architecture has difficulty in balancing the network load, often leading to congestion and increased latency. The centralized controller, overloaded with content requests, faces the risk of becoming a bottleneck, thereby reducing the network's overall throughput. Addressing these issues requires innovative controller designs, improved algorithms for content discovery and caching, and robust security mechanisms for ICN-IoT paradigm.

The majority of ICN-IoT solutions face scalability challenges as the number of contents significantly exceeds the capacities of diverse IoT devices and applications [18]. For example, the hierarchical namespacing of content and the in-memory size of ICN routers necessitate efficient naming and optimization solutions. These are required to alleviate transmission delays and storage inefficiencies. Besides, standardizing northbound APIs is crucial for improving communication and stimulating innovation in software without hardware modifications. Specifically, developing RESTful APIs that meet precise constraints and robust authorization mechanisms is essential for enhancing service portability and interoperability [19]. Due to dynamic mobility between producers and consumers, applying machine learning (ML) techniques, such as deep learning, is essential to enable intelligent content forwarding and caching strategies [20], [21]. This introduces further complexities due to their heterogeneous composition and fluctuating channels, necessitating advanced and integrated approaches using ICN, SDN, and network function virtualization (NFV). Caching in ICN-IoT networks faces challenges in meeting low latency, resource utilization, and QoS

requirements of heterogeneous applications [22]. Similarly, the repeated caching of popular content for user groups with shared interests requires intelligent and scalable solutions. Furthermore, network slicing via NFV facilitates parallel handling of tasks, necessitating integration with dynamic caching strategies and content-centric routing to adapt to dynamic IoT conditions [23]. Hence, existing solutions must leverage these technologies to advance the efficiency of ICN-IoT. In addition, more research is needed into consolidated frameworks that jointly optimize caching, routing, and network virtualization in accordance with application-specific demands. This integration is pivotal to the progression of IC-SDN efficiency and functionality within the context of IoT networks.

To address these issues, a communication module is proposed that incorporates an IC-SDN controller and ICN routers to enable efficient content management and scalable forwarding in the softwarized clean-slate ICN-IoT system. Specifically, the IC-SDN controller is designed to collect essential information from ICN routers during the bootstrapping phase. This information includes the network topology, the number of nodes (e.g., consumer, ICN router, producer), and path-related metrics. The controller is also configured to obtain available content names from each node, enabling effective distribution and management throughout the network. In response to new content requests, consumers are instructed on how to establish connections with the ICN router, typically providing a link to the producer. Subsequently, the controller calculates the optimal path and installs the necessary flows into the corresponding ICN routers to retrieve the requested content. In essence, our work addresses the challenge of processing multiple content requests simultaneously, which affect the controller's performance in terms of flow processing time, average delay, and response rate.

The main contributions are summarized as follows:

- A novel ICN packet structure is introduced, which features modified TLVs to facilitate IC-SDN communication within IoT systems. More specifically, custom-defined TLV components have been developed to create new types of request (*Req_Pkt*) and response (*Res_Pkt*) packets. This packet structure orchestrates scalable inter-layer communication between participating nodes to enhance content delivery efficiency and reduce communication overhead.
- Graph theory is applied to the proposed IC-SDN controller to achieve a global view of the network topology and optimize content distribution within the ICN system. This enables the controller to identify the most efficient routes for data flow and guide various nodes, such as consumers (e.g., IoT devices), producers (e.g., remote servers, data centers), and ICN routers.
- A PIT-centric forwarding mechanism is proposed to address the overhead limitations of existing IC-SDN architectures. This mechanism aims to improve content retrieval times as the number of requests and content volume grow. By dynamically assigning caching responsibilities to specific intermediate ICN routers based on the initial consumer request, the proposed approach promotes a scalable and adaptable content distribution and

management system.

- The performance of the proposed solution is evaluated through simulation-based studies and numerical analysis. These evaluations demonstrate that the novel PIT-centric forwarding mechanism significantly reduces forwarding overhead. Additionally, the logical decision-making capabilities of the controller enhance dissemination between the consumer and producer, regardless of their placement within the system.

The remainder of the paper is organized as follows. Section II discusses the related work highlighting the motivation behind this study while Section III presents the layered architecture of the proposed CIC-SIoT solution alongside its fundamental components. Besides, Section IV introduces the implementation and working principle of CIC-SIoT, including packet structure, workflow of the participating nodes and their communication principle. Furthermore, Section V discusses the proof-of-concept implementation and performance evaluation against the baseline solutions. Finally, Section VI concludes the paper recalling the primary contributions and hinting the future work.

II. RELATED WORK

The ongoing research shows that the inherent benefits of integrating ICN in a softwarized network make it a suitable networking model for various emerging technologies, such as the IoT, Internet of Vehicles (IoV), and 5G [17], [22], [24]. Previous works have focused on the integration of ICN and SDN, aiming to merge the solutions for multipath routing, cooperative caching, flow processing, and holistic network management. These innovations emphasize the strategic overlay of control and caching mechanisms to enhance data delivery and network management.

In terms of multimedia transmission optimization over 5G networks, Zhang and Zhu *et al.* [25] propose an integrated solution that merges ICN for optimal in-network caching, NFV for abstracting physical infrastructures, and SDN for dynamic resource allocation to ensure quality of service in wireless networks. Although, the approach improves statistical delay-bounded QoS for multimedia big data services, the reliance on extensive virtualization introduces complexities in deployment and scaling, particularly in environments with variable network conditions. Likewise, Amadeo *et al.* [26] focus on the orchestration of computing services in edge networks. The authors leverage SDN's centralized intelligence for service allocation and NDN's adaptive forwarding and caching to manage services by name. Their framework excels in reducing service provisioning delays by integrating network and computing resource management. Nevertheless, the intensive requirements for centralized control impact scalability and adaptability in highly distributed networks.

Regarding traffic engineering (TE) [27] optimization, Zhang *et al.* [28] apply deep learning (e.g., Deep Reinforcement Learning) into an IC-SDN scenario to enhance content-aware network management. While their demonstration shows significant improvements in network throughput and balance, the practical application of AI techniques in TE poses challenges

due to the inherent complexity and dynamic nature of real-world networks. On the other hand, Benedetti *et al.* [29] present an integration of ICN, multi-access edge computing (MEC) [30]), and SDN to improve the management of mobile networks, particularly targeting the challenges of mobile consumer connectivity. The authors propose a protocol architecture to reduce communication overhead and increase network efficiency. However, the integration complexity and heavy reliance on advanced, coordinated functionalities across different network layers limit rapid deployment and flexibility.

As for adaptive caching in ICN-IoT, Sharif *et al.* [31] propose a sliding window-based model and a neural prediction module for dynamically adjusting to changes in data popularity. This approach significantly reduces energy consumption and response times. A limitation of their work is the assumption of consistent and accurate popularity predictions, heavily depends on the accuracy and timeliness of the popularity predictions. This presents a challenge in highly dynamic IoT environments. In addition, Khalid *et al.* [32] address the challenges of mobile adhoc networks (MANETs) in the context of NDN and SDN. The authors propose a routing protocol that considers node mobility and energy levels to improve communication reliability and efficiency. Although, their result show reduced retransmissions and enhanced data retrieval times, the reliance on a single controller introduces bottlenecks and limits scalability in larger network setups.

In the context of IC-SDN applicability in smart city environment, Demiroglou *et al.* [33] explore an adaptive multi-protocol system to maintain low latency and high reliability by intelligently switching between NDN, delay-tolerant network (DTN), and a combined scheme based on network conditions. This innovative approach ensures robust performance under varying urban network conditions. However, it faces challenges in standardization and interoperability across different network protocols. Furthermore, Anjum *et al.* [34] tackle the deterministic delivery challenges in NDN for IoT by integrating a deadline-aware schedulability algorithm. They significantly enhance the timeliness of critical data delivery. While the specific focus on deadline-aware scheduling is advantageous for time-sensitive applications, broader application requires more generalized network management strategies to handle diverse IoT traffic patterns effectively.

Several solutions have been proposed to enhance the integration of SDN and ICN, focusing on the modification or extension of existing packet structures, protocols, and architectures. For example, Sun *et al.* [36] introduce an SD-CCN solution with an OpenFlow switch, a CCN router, and an extended SDN controller on top of the existing NOX controller [37] to process CCNx [38] packets using custom TLV match fields. The approach enhances multipath routing, traffic management, and content-based forwarding but lacks evaluation of flow processing efficiency and content caching. Besides, Son *et al.* [39] propose a forwarding solution with distributed SDN controllers managing PIT and FIB functionalities from ICN, improving content awareness by modifying packets. However, the solution lacks a clear approach for content caching and distribution. Moreover, Gao *et al.* [40] focus on scalable forwarding and caching using multiple controllers in a multi-

Table I: Comparison between related works

References	ICN/NDN Enhancements		SDN Controller Enhancements		Inter-domain Content Distribution	Source code Availability
	Clean-Slate Design	Packet Modification	Multi-path Routing	Caching Awareness		
[25]	×	×	✓	✓	✓	×
[26]	×	✓	✓	×	×	×
[28]	✓	×	✓	✓	×	×
[29]	×	×	✓	×	✓	✓
[31]	×	×	×	✓	✓	×
[32]	✓	✓	✓	×	×	×
[33]	×	×	✓	×	✓	×
[35]	×	×	✓	✓	×	×
Our Work	✓	✓	✓	✓	✓	✓

domain environment. While handling interactions through essential services, this solution overlooks content caching prioritization and new content request allocation, potentially leading to slower response rates. Likewise, Torres et al. [41] implement a centralized controller for routing decisions and reducing ICN routers' storage consumption, but the scheme suffers from increased hand-off latency during high flow rates. Meanwhile, Jmal et al. [42] incorporate OpenFlow switches into the content-centric system using controller-based forwarding and caching with CCNx and BGP principles. Although performance evaluation is initiated, the integration principle for BGP-based routing and caching coordination is not fully explained. Additionally, Lv et al. [43] address scalability by segregating ICN into clusters based on content type similarity and assigning distributed controllers for content tasks. The solution aims to improve forwarding flexibility and content retrieval but lacks details on load balancing, QoS support, and controller interaction. Furthermore, Chen et al. [35] integrate SDN with ICN as an overlay to tackle cooperative caching, bandwidth, and resource allocation in large distributed environments. The approach, involving SDN controllers, OpenFlow switches, and ICN routers, shows promise with simulated results highlighting minimal energy consumption and efficient content aggregation. However, it remains theoretical with limited practical details.

Regarding ICN-IoT deployments in Wireless Sensor Networks (WSN) scenarios, existing solutions face challenges such as data dissemination efficiency, reliability, and scalability. For example, CCIC-WSN [44] faces limitations in scalability and flexibility due to its reliance on a static cluster hierarchy. This structure leads to bottlenecks at cluster heads, especially in dynamic environments characterized by frequent node mobility and fluctuating data demands. Similarly, CIDF-WSN's [45] reliance on the Neighbor Information Base (NFIB) for next-hop selection becomes complex and resource-intensive as the network density increases. This is because NFIB requires maintaining a comprehensive list of virtual faces with associated costs for all nodes within the transmission range. This task grows increasingly demanding regarding computational and storage resources in densely populated networks.

Our proposed solution addresses these limitations by adopting a multi-layered, distributed control mechanism that significantly enhances network scalability and flexibility, enabling dynamic adaptation to varying network conditions and de-

mands. Unlike the existing works, our architecture is designed to efficiently manage single- and multi-interface environments, ensuring optimal performance across a broader range of IoT scenarios. While many studies have explored packet structures, our approach emphasizes refining these structures to enhance the packet identification and decision-making capabilities of the controller. Furthermore, the proposed controller operates using distributed logic, ensuring optimal data routing even while being physically centralized. We have introduced a new packet format aimed at improving communication scalability and efficiency, thereby addressing challenges that prior research has either neglected or only touched upon briefly. In addition, in accordance with the specifications outlined in RFC 9138 [46], this study systematically tackles the challenges associated with name resolution in the context of system scalability, manageability, deployment considerations, and fault tolerance capabilities. Table I shows a comparison between this work and the state-of-the-art solutions for the listed challenges.

III. SYSTEM ARCHITECTURE

This section presents a technical overview of the proposed architecture alongside the necessary components and their workflow. First, we present a brief overview of the proposed architecture that focuses on the softwarization of the information-centric clean-slate packet transmission principle. Then, a detailed overview of the proposed packet modification is given, along with the impact of the packet structure on the overall system. Finally, we present a technical overview of each component of the proposed architecture.

A. Layered Overview of the Architecture

In a traditional SDN system, the controller communicates with forwarding devices. However, in a typical ICN, there is no central or distributed control logic to manage participating ICN routers [12]. Instead, underlying ICN routers forward and cache desired content in a stateful manner based on the consumer's intention, unlike the stateless communication between data-plane devices in SDN [17]. The proposed solution incorporates both principles of SDN and ICN to forward and cache multiple content chunks based on specific instructions from the control layer. Specific flow instructions are determined by the service type, depending on the application or service that the consumer requests from the control layer. The layered

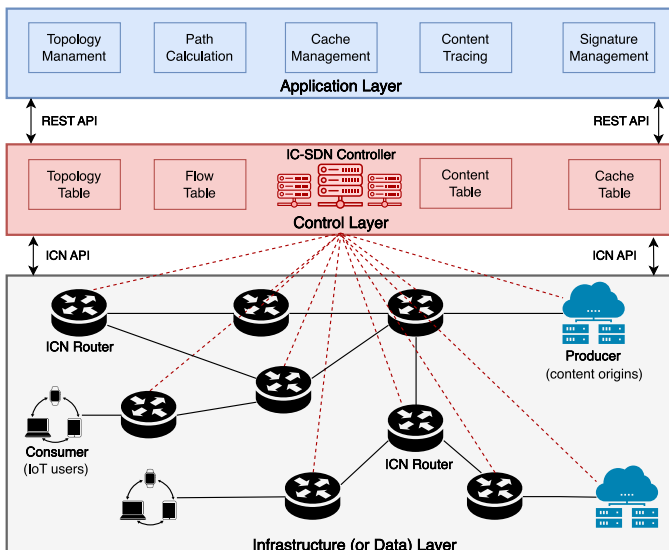


Figure 1: Proposed system architecture.

architecture of the proposed scheme is shown in Figure 1, which is divided into application, control, and infrastructure (or data) layer. The architecture employs two types of application programming interfaces (APIs) – ICN API [47] and REST [19]. The ICN API enables the controller to communicate with other ICN routers in the infrastructure layer, while the REST API provides high-level programmability abstraction between the application and control layer. The APIs enhance the proposed CIC-SIoT principal to be compatible with both distributed flat and hierarchical controllers. However, detailed implementation and working principles of distributed controllers are left for our future work. The control layer features a centralized IC-SDN controller that is distributed and has multiple instances. This allows hyper-scalability and removes the single-element bottleneck. The synchronization among the instances is not trivial. However, existing solutions for distributed server management can be applied. The control layer manages and orchestrates all nodes in the network. The infrastructure layer accommodates consumers, ICN routers, and producers (such as content origins or data centers).

On the other hand, the application layer in our proposed IC-SDN architecture serves as a critical intermediary between high-level application requirements and the network’s control plane. This layer bridges the gap by harmonizing SDN’s programmability with ICN’s data-centric approach to foster seamless integration. It empowers applications to interact with the network based on data names rather than relying on traditional location-based methods. The RESTful or REST APIs fulfill a dual function – upholding SDN’s core principles of abstraction and programmability while facilitating ICN’s content-oriented communication. Applications, for instance, leverage these APIs to instruct the IC-SDN controller to compute optimal delivery paths for managing content caches across the network and tracing the flow of named content for diagnostics or optimization. Furthermore, the application layer ensures that the control logic provided by the IC-SDN controller aligns with ICN’s objectives. These objectives include

efficient content dissemination, enhanced security by binding security measures directly to the content itself and providing a diverse range of content-oriented network services. Through REST API interfaces, application layer modules like topology management, path calculation, cache management, content tracing, and signature management instruct the IC-SDN controller to align network resources with data-centric operations. This includes mapping data names to network paths, managing distributed content caches to minimize latency, tracing content for improved network visibility, and implementing named-based security measures for data integrity and authentication. The REST APIs abstract the complexities to allow applications to seamlessly request and control network services, ensuring an adaptive, efficient, and secure data flow across the IoT landscape.

B. Overview of Controller

In traditional ICN, the decision making of some critical tasks such as caching and forwarding of the contents are assigned to ICN routers. However, we design our controller to take control of some of these tasks. Therefore, the controller is the most vital entity in our solution. Before making all the forwarding and caching decisions, the controller is responsible for maintaining two essential tables. The first one is the content table, where it stores the contents’ names along with the producer id. Therefore, the controller is aware of the content along with their location. On the other hand, after receiving the necessary information from ICN routers from the data layer, such as their active faces and neighboring nodes, the controller builds a graph of the entire topology. In later stages, the controller is also required to calculate the available path’s weight to find the most optimal path to allow the forwarding the most efficient way. We discuss the path calculation method in more detail in the next section.

C. Overview of ICN Router

The ICN router in our framework has multi-folded functions in terms of forwarding and caching capabilities. Firstly, the ICN routers with the built-in caching capability preserve necessary contents and make them available based on the controller’s instructions. Secondly, ICN routers with non-caching capabilities participate in a request-response message exchange with the controller. The exchange allows the content to move from the producer to the consumer and behaves more like an SDN-based switch. The primary task of these nodes is to find the interfaces (e.g., incoming and outgoing) for each intermediate ICN router and to update the PIT entries based on the optimal path from the consumer to the producer.

D. Overview of Consumer

In our framework, the consumer acts as a data requester, initiating the content retrieval by broadcasting an interest packet. Unlike IP-based systems, where data is retrieved from a specific source, conventional ICN architectures (e.g., NDN) handle the interest packet by the network of routers. These routers return the data from any location where it is

cached, enhancing robustness against individual link failures. To further improve reliability and efficiency in our design, the consumer leverages the proposed packet structure (shown in Figure 2), enabling it to maintain communication with multiple ICN routers and the controller. If an intermediate router fails or does not respond, our system’s controller promptly identifies and redirects to an alternative path to mitigate any negative impact on content retrieval rates. Therefore, while our consumers operate within the ICN paradigm, they benefit from enhanced reliability through a design that supports dynamic rerouting by the controller.

E. Overview of Producer

The producer in the solution acts as the primary source of the content. Therefore, it can either be a data center or a remote server with the original version of the content. The producer also validates the signature of each content it contains. The primary difference between the traditional ICN producer and our proposed producer remains on how it connects to the controller despite its location. In the initial phase, the producer prepares a *Req_Pkt* for the controller to share the content’s necessary information, including name, location, signature, and path to the producer. Once it receives the *Req_Pkt* from the controller, it prepares the data with signature and forwards it to the ICN router.

IV. IMPLEMENTATION AND WORKING PRINCIPLE

In this section, we provide necessary technical details of the proposed packet structure alongside the specific implementation, including the workflow and algorithms of individual nodes such as controller, intermediate nodes, consumer, and producer. We begin by providing an overview of the integrated components of the TLV structure of the proposed *Req_Pkt* and *Res_Pkt*. Then we present each participating node individually with their novel working principles.

A. Proposed Packet Structure

In general, every ICN packet is encoded in a Type-Length-Value (TLV) format which helps the existing packets (e.g., interest or data) to be distinguished by their behavior and functionalities. Hence, the TLV structure of ICN-based implementations, i.e., CCN or NDN can be different. For example, CCN supports fixed-length TLVs for its packet structure and data-plane parsing capabilities [38], while NDN uses nested variable TLVs, composed of sub-TLVs. Each of those values, type, and length from sub-TLVs offer variable size [48]. This makes the modification and customization of NDN packets to be more challenging. Despite the complexities of TLV modification, it allows customized ICN name tag with necessary objects which can be embedded inside a packet. Previous IC-SDN solutions [49]–[51] propose TLV modifications to enable compatibility between ICN packet structure, OF switch, and the SDN controller. For example, Signorello et al. [50] separate nested-TLV sequence of NDN *Int_Pkt* and *Dt_Pkt* into separate header fields and payloads so that the P4 [52] data plane parser can process them individually. Although the

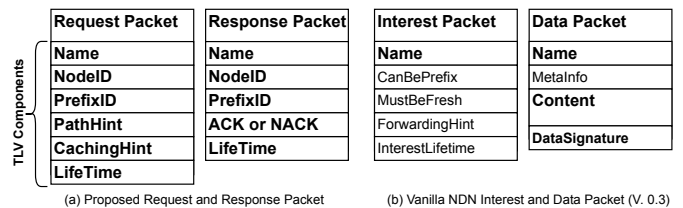


Figure 2: Proposed packet structure in CIC-SIoT.

implementation promises to tackle compatibility between SDN and ICN, having different field values leads to performance overhead and portability issues.

To overcome these challenges, we propose a novel packet structure to allow the controller to communicate with other nodes by forwarding necessary instructions in the form of modified flows. As shown in Figure 2, the proposed packet structure consists of a request packet (*Req_Pkt*), and a response packet (*Res_Pkt*). To ensure the feasibility and effectiveness of our approach, we add necessary service-related objects wire-encoded as TLV into the *Req_Pkt* and *Res_Pkt*. The concept is inspired from the *flow_mod* messages – one of the variations of available TLV architecture that the traditional SDN controller regularly uses alongside *packet_in* and *packet_out* messages [53]. The specifications of our custom-defined TLV objects are illustrated as follows:

- **Name:** Serves as the unique identifier for the content. Consumers use this object to identify desired content, while producers utilize it to advertise available content. For intermediate ICN routers, the object’s representation varies depending on caching capabilities. ICN routers with caching capabilities carry the cached content names; otherwise, they ignore this object.
- **NodeID:** Acts as a unique identifier for active nodes within the data layer. It significantly enhances network efficiency and reliability. NodeIDs are crucial for streamlining content retrieval and optimizing routing as the proposed IC-SDN controller maps the requested content names to the appropriate NodeID. This can be either the NodeID of the original producer or the nearest caching node. This mapping facilitates optimal delivery path decisions, considering factors such as network congestion, node availability, and geographic proximity to the consumer. NodeIDs are particularly advantageous in environments characterized by high mobility or frequent content updates as they enable the controller to rapidly adapt routing paths [54]–[56].
- **PrefixID:** The fundamental ICN feature that helps the controller track and record requests from consumers across different locations.
- **PathHint:** Deployed by the controller to direct ICN routers towards facilitating content retrieval along the most optimal paths. The controller embeds this hint in the *Req_Pkt* after calculating the optimal routes to assist ICN routers in setting up the necessary forwarding paths.
- **CachingHint:** Used by the controller to inform ICN routers about the availability of cached content, promoting efficient delivery within the network.

Table II: Notations used in the Paper.

Symbol	Representation
$\mathcal{G} = (\mathcal{V}, \mathcal{E})$	Topology (as undirected graph), nodes, and links between nodes
$\mathcal{C} = \{1, \dots, C\}$	Set of Controllers where each controller $c \in \mathcal{C}$
$\mathcal{N} = \{1, \dots, N\}$	Set of ICN routers where each router $n \in \mathcal{N}$
$\mathcal{U} = \{1, \dots, U\}$	Set of IoT users where each user $u \in \mathcal{U}$
$\mathcal{S} = \{1, \dots, S\}$	Set of producers where each producer $s \in \mathcal{S}$
x, y	TLVs, packet
$x_{id}, x_{pre}, x_{node}, x_{path}, x_{tag}, x_{data}, x_{sig}$	ID, prefix, node, path, tag, payload, signature
$y_{int}, y_{data}, y_{req}, y_{res}$	Interest, data, request, response packets

Algorithm 1: Discovery and distribution.

```

1 Function COLLECT Path from  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ 
2   forall  $y_{req}$  from  $\mathcal{N}, \mathcal{S} \in \mathcal{V}$  do
3     // here  $y_{req}$  is incoming
4     Read  $y_{req} = (x_{name}, x_{pre}, x_{node}, x_{tag})$ 
5     while  $x_{node} = s$  and  $s \in \mathcal{S}$  do
6       Topology Table  $\leftarrow$  Add or Update  $x_{node}$ 
7       Content Table  $\leftarrow$  Insert  $x_{name}, x_{pre}$ 
8        $\mathcal{S} \leftarrow$  Forward  $y_{res}(x_{tag})$  with ACK
9     while  $x_{node} = n$  and  $n \in \mathcal{N}$  do
10      Topology Table  $\leftarrow$  Add or Update  $x_{node}$ 
11      Cache Table  $\leftarrow$  Insert  $x_{name}, x_{pre}$ 
12       $\mathcal{N} \leftarrow$  Forward  $y_{res}(x_{tag})$  with ACK
13
14 Function INSTALL Path to  $n \in \mathcal{N}$ 
15 forall  $y_{req}$  from  $\mathcal{N} \in \mathcal{V}$  do
16   Read TLV  $y_{req} = (x_{name}, x_{pre}, x_{node}, x_{tag})$ 
17   while  $x_{node} = n$  and  $n \in \mathcal{N}$  do
18     Content Table  $\leftarrow$  Lookup  $x_{name}, x_{pre}$ 
19     if Lookup = Successful then
20       // map shortest path
21        $\mathcal{E}_{CS} \cup \mathcal{E}_{CN} \cup \mathcal{E}_{NS} \cup \mathcal{E}_{NU} \leftarrow$  Apply
22       Optimal Path
23       // here  $y_{req}$  is Outgoing
24        $\mathcal{N} \leftarrow$  Forward  $y_{req}(x_{path}, x_{tag})$ 
25        $\mathcal{S} \leftarrow$  Forward  $y_{res}(x_{tag})$  with ACK
26     else if Lookup  $\neq$  Successful then
27       Pending Table  $\leftarrow$  Insert
28        $x_{name}, x_{pre}, x_{node}$ 
29        $\mathcal{N} \leftarrow$  Forward  $y_{res}(x_{tag})$  with NACK

```

Algorithm 2: Caching and forwarding strategy.

```

1 Function UPDATE and RANK (PIT entries)
2   forall  $y_{req}$  from  $\mathcal{C}, \mathcal{U}, \mathcal{S} \in \mathcal{G}$  do
3     Read TLV  $y_{req}(x_{name}, x_{pre}, x_{tag})$ 
4     while  $x_{node} \in \mathcal{C}$  do
5       PIT  $\leftarrow$  Insert  $(x_{name}, x_{pre}, x_{tag})$ 
6        $\mathcal{C} \leftarrow$  Forward  $y_{res}$  with ACK
7     while  $x_{node} \in \mathcal{S}$  do
8       PIT  $\leftarrow$  Insert  $(x_{name}, x_{pre}, x_{tag})$ 
9        $x_{data} \leftarrow$  Validate Signature
10      CS  $\leftarrow$  Add or Update  $(x_{name}, x_{pre}, x_{tag})$ 
11       $\mathcal{S} \leftarrow$  Forward  $y_{res}$  with ACK
12     while  $x_{tag} \in \mathcal{U}$  do
13      CS, PIT  $\leftarrow$  Lookup  $y_{req}(x_{name}, x_{pre}, x_{tag})$ 
14      if Entry exists then
15         $\mathcal{U} \leftarrow$  Forward  $y_{res}(x_{pre}, x_{pre}, x_{tag})$ 
16      else
17         $\mathcal{N}, \mathcal{S} \leftarrow$  Forward
18         $y_{req}(x_{name}, x_{pre}, x_{tag})$ 

```

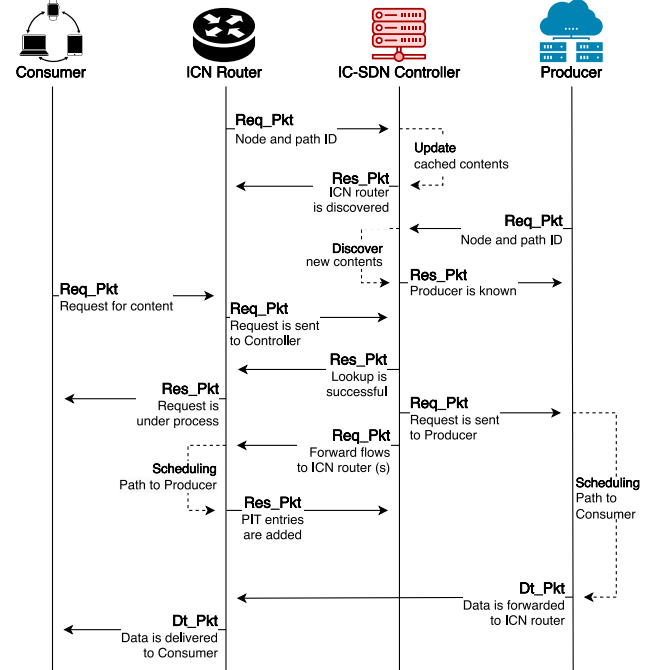


Figure 3: Discovery and distribution procedure in CIC-SIoT.

- **(N)ACK:** Stands for positive or negative acknowledgment and is a fundamental component of the *Res_Pkt*. It notifies the source node of the outcome of the requested content or service.
- **LifeTime:** Defines how long the *Req_Pkt* and *Res_Pkt* remain active or pending at the controller, ensuring timely processing and expiration of requests.

B. Communication Principle

The communication method (shown in Figure 3) is divided into two phases – i) discovery (or bootstrapping) phase, and ii) allocation (or distribution) phase. Firstly, we discuss the discovery of available contents which allows the proposed

controller to discover the contents in local and global regions. Later, we describe the content allocation model which discuss on the content dissemination process in CIC-SIoT system. The discovery and distribution algorithm is presented in Algorithm 1.

1) *Discovery Phase:* In the discovery phase, all available producers in the topology sent their prefix information to the controller. After receiving this information, the controller stores them into a table. The communication process between a controller and multiple producers initializes in the discovery phase. The controller acknowledges the available contents and their location immediately. The finite state machine (FSM) representation of all the participating nodes is shown in

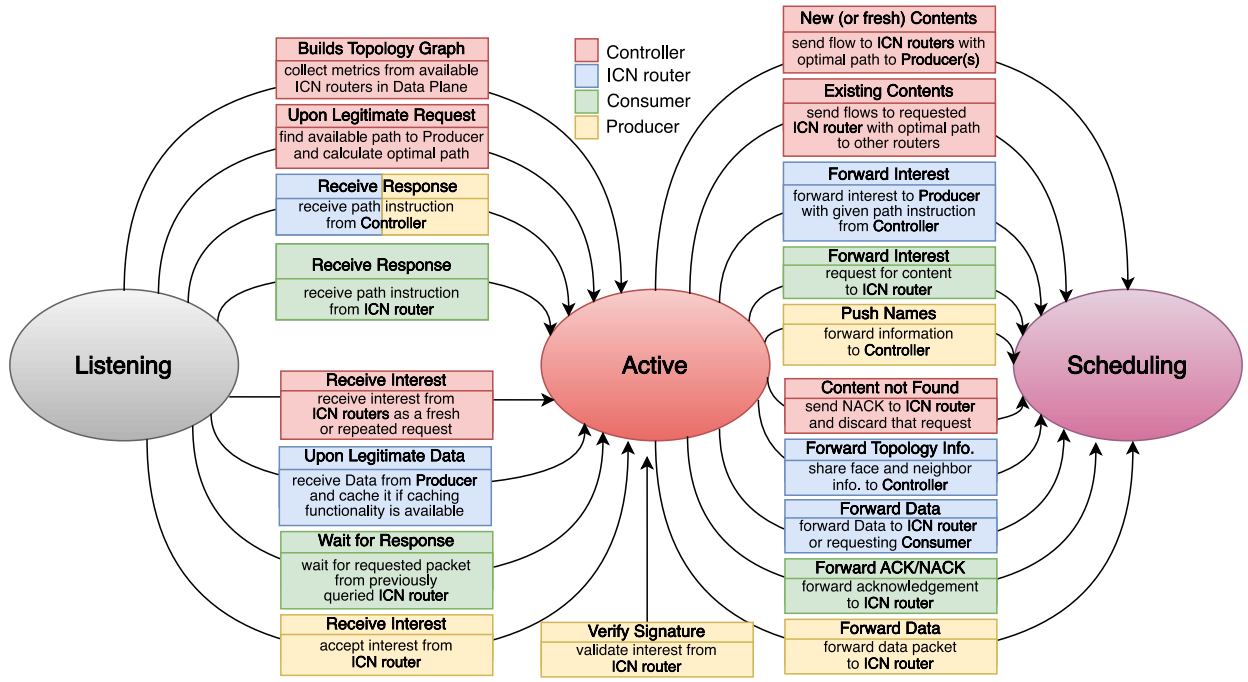


Figure 4: Task FSM of Controller, ICN router, Consumer, and Producer.

Figure 4.

In the network topology, as producers are integrated, they automatically transmit their content names to the controller. A push-based method is adopted over a pull-based approach to mitigate the potential overload on the controller from continuous content availability inquiries from producers. The TLV modifications enable the precise routing of *Req_Pkt* and *Res_Pkt* for specific operations, ensuring efficient content discovery and routing. The hierarchical namespace allows the specific prefix to build an automated service-oriented forwarding using distributed controllers. On the other hand, the application running under each producer allocates content using a specific namespace. For example, “*ndn://domain_id/producer_node/content_name/segment_number/version*”. This allows the controller to recognize the location of the content during the discovery period. After receiving contents from different producer, the controller stores those names in the *content_records*. To implement such data structure, we add a vector table to list contents’ origin and to guide the controller discovering the producers with those available contents. During the discovery phase, the ICN routers send necessary information that includes bandwidth, metric, delay and queue to the controller. To allow transmitting such type of information, we have made changes on ICN router in accordance with the NDN paradigm. Note that, the controller is maintaining two different data structure. The first one represents the name of the contents from the producer and the second one represents the information of each ICN router.

2) *Distribution Phase*: The controller register the name of the content along with *node_tag*, content name and the timer into its *content_records*. If the content is not requested for 30 seconds then the entry from table is deleted but

if content is requested then timer incremented. The critical decision making initiates while it receives a *Req_Pkt* from the consumer for a the desired content. The controller extracts the TLV components of that *Req_Pkt* and looks upon the *content_records* and *cache_entries*. If the name is found on the *content_records* instead of *cache_entries*, the controller looks for the producer associated with the name of that desired content. After searching content the controller calculate the most optimal path using Dijkstra to find the best optimal route from the requested Consumer to the Producer that has that content. Correspondingly, the controller sends *Req_Pkt* with flow instruction that would populate the PIT entries of those nodes that are in that path. Afterward, the controller make connection status table as two communicating nodes never interrupted. The controller guides the ICN nodes based on whether certain contents are cached or not. For example, if specific contents are available in different ICN nodes, the controller registers those contents’ prefixes in its *cache_entries* to keep track of them. Upon receiving a request, the controller looks up the content’s name on the *cache_entries* to identify the *node_tag* of the intermediate ICN router with the requested content. Afterward, it calculates the available paths from the consumer to that ICN router using Dijkstra to define the best optimal path. Suppose the intermediate ICN nodes do not cache the requested content. In that case, the controller discovers the *Producer_ID* and other intermediate *Node_IDs* to calculate the shortest route from the consumer with the requested content to the producer. Hence, the controller forwards *Req_Pkt* with flow instructions to all those intermediate ICN nodes by populating PIT entries. Finally, the controller forwards *Res_Pkt* to the initial ICN node on the path to guide other ICN nodes to shift the desired data to the requested origin. The caching and forwarding strategy of the proposed

CIC-SIoT is shown in Algorithm 2.

V. PERFORMANCE EVALUATION

In this section, we evaluate the proposed CIC-SIoT implementation using simulation study to demonstrate the efficiency of the controller. Firstly, we categorize the performance evaluation section into two sub-categories, i.e simulation-based performance analysis and numerical analysis. In the simulation-based analysis, we use a physical testbed using a single workstation. The hardware specification is similar to the one used in [57], [58]. We use a heavily modified version of ndnSIM [59] to execute all the simulation-related experiments. The experimental parameters are mentioned in Table III. We first present the technical details of our proposed solution as a proof of concept implementation in the opening portion of this section. Then we give a brief technical overview of the testbed environment that has been used to conduct all the experiments to evaluate the performance of our proposed CIC-SIoT framework. Next, we present the simulation parameters of the simulation-based experiments. Finally, we discuss in details regarding the result analysis from the simulation-based analysis. We conclude the section by presenting the result from the numerical analysis. MATLAB [60] is used in the numerical analysis to show the feasibility of the solution while comparing against some of the recent works in IC-SDN implementation.

A. Proof of concept Implementation

Here, we give a brief overview on the proof of concept implementation of our proposed solution, which includes packet modification, simulator library files, topology for simulation and custom-designed applications for the main modules such as consumer, producer, controller, and ICN router. Sources of the proof of concept implementation are provided in Github¹. We utilize ndnSIM [59] to deploy the IC-SDN framework as it is widely used for simulating NDN based projects. It is developed as an additional module of ns-3 [61].

The ns-3 integration allows ndnSIM to take advantage of the available abstraction, function, and simulation module. The current version of ndnSIM improves the integration with real-world NDN codebase like ndn-cxx [62] and NFD [63] library that enable the abstraction for fundamental NDN and ICN tasks such as named content transmission, encoding or decoding of named packet and security-based implementation. To utilize the simulation environment to its maximum potential, we make changes on both packet level and application level. Packet level changes include addition and modification of TLV values through customizing ndn-cxx libraries. Besides, we also make some minor changes on *helper model* and *NFD forwarder*. Afterward, we designate individual application module for the controller, information-centric ICN router, custom consumer and producer.

B. Overview of Simulation Testbed and Parameters

To evaluate the performance of our proposed system, we use a custom-designed topology alongside the widely used Rocketfuel topology [64]. The structure of both these topologies is

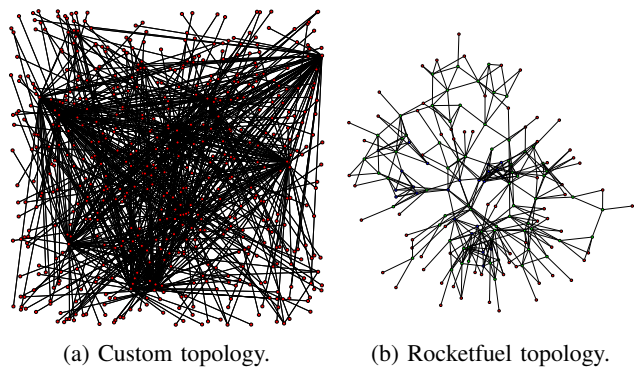


Figure 5: Topologies used in the simulations.

Table III: Simulation parameters and their specifications.

Parameter	Specifications
Topology	Custom, Rocketfuel [64]
Link delay	10 ms
Link bandwidth	1 Gbps (core and access)
PIT size	10,000 entries
Number of contents	100 to 300
Number of caching nodes	100
Request rate	20 to 100 interests/sec.
Payload size	1024 bytes
Popularity rate	Zipf ($\alpha = 0.80$)
Forwarding strategy	Best route and multicast
Caching strategy	LCD
Simulation duration	60 sec. to 10 minutes

shown in Figure 5. Our simulation testbed is structured into a three-layer custom topology, reflecting the hierarchical nature of large-scale networks. The control layer includes multiple instances of our IC-SDN controller, each embedded with algorithms for path discovery and content distribution. The core layer comprises 50 routers that serve as intermediaries, facilitating communication between the producers and the control layer. The access layer includes 20 routers proportionally distributed among the consumer nodes. Each access router provides connectivity for a cluster of 25 consumers, collectively supporting 500 consumers. It is important to note that ICN routers in the core layer have in-network caching capabilities, whereas the access nodes are non-caching forwarding nodes, similar to SDN-based OF switches [65]. We set the link capacity of core and access nodes randomly in the range of 500 Mbps to 1 Gbps. All consumers generate data (or content) at a rate of 100 Mbps. The link between the producer and core node is set to 10 Mbps, and the propagation delay of the available links is set to 1 ms. Due to the initialized path and caching hint on the *Req_Pkt*, the header size may slightly differ, including optional and static TLV headers. Therefore, the encoded data, packetized into a set of *Res_Pkt*, may vary in size than the maximum transmission unit (MTU). As a result, we defined the size of the *Req_Pkt* and *Res_Pkt* as 200 and 1028 bytes, respectively. Each experiment is executed 30 times to maintain a confidence level of 95% and avoid possible randomness and errors, obtaining an averaged calculation for the statistical analysis of the proposed and baseline solutions.

¹<https://github.com/karimmd/ndnSIM-PIT>

C. *ndnSIM*-based Results Discussion

In this section, we provide a detailed analysis of the experimental results. We evaluate our proposed CIC-SIoT solution using four key metrics: (i) throughput, (ii) flow installation, (iii) caching efficiency, and (iv) packet loss. Firstly, we define throughput as the rate at which our system successfully delivers data to each consumer, serving as a primary indicator of network performance. Moreover, we measure the flow installation rate, which reflects the IC-SDN controller's efficiency in initiating network traffic flows. Besides, we assess caching efficiency by determining how effectively data can be retrieved from ICN router caches, which measures the network's capacity to reduce the burden on content producers. On the other hand, we calculate packet loss as the ratio of lost packets to total transmitted packets, thereby providing a critical measure of network reliability. To conduct the evaluation, we use separate simulation scripts for four different experiments, all using the topologies shown in Figure 5. However, extensive experimentation shows that the topological change has an insignificant impact on the results. Figure 6 shows that the throughput (further explained in sections below) is almost the same for both topologies; hence, we have presented the average results from both in the later sections.

1) *Throughput Analysis*: We measure throughput up to 500 consumers for both traditional NDN implementation and our proposal. We execute this experiment to showcase the level of successful contents delivery from consumer to producer. It is worth mentioning that, either packet loss or network congestion can have a detrimental impact on throughput. We obtain the number of total packet counts and divide them with the total number of consumers to obtain the average throughput rate into bits per second. Then we convert them into Mbps for better presentation. To measure the throughput rate (TR) for each consumer, we use $TR = TPC/NoC$ where number of consumer and total packet count are denoted as NoC and TPC, respectively. Figure 7a shows the throughput evaluation between standard NDN-based implementation and proposed CIC-SIoT prototype. The traditional NDN implementation achieves an average throughput from 1 Mbps to 10 Mbps for 10 to 500 consumers. On the contrary, the proposed CIC-SIoT solution shows constant performance increment as we increase the consumers from 10 to 500. As for 10 consumers, the framework achieves 1 Mbps, and later the performance rises above the traditional NDN by reaching up to 20 Mbps for 500 consumers. The IC-SDN framework achieves the maximum

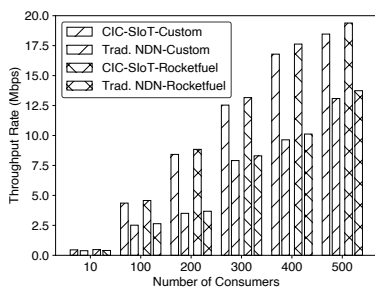


Figure 6: Throughput comparison for different topologies.

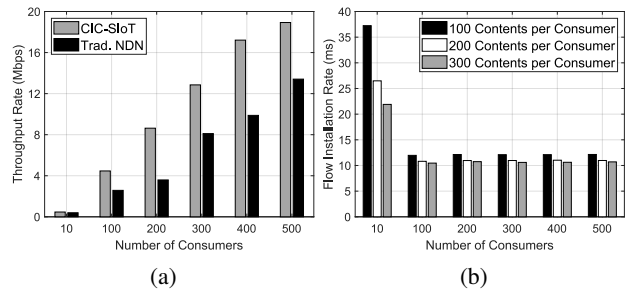


Figure 7: Performance analysis of (a) throughput and (b) flow installation rate

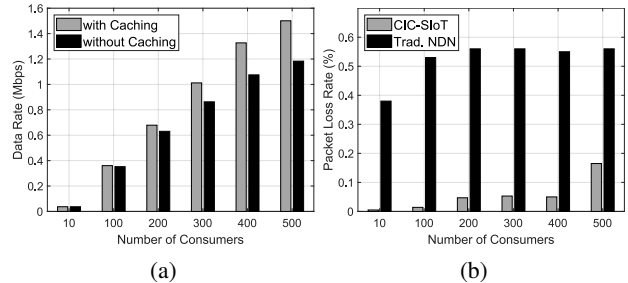


Figure 8: Performance analysis of (a) caching efficiency, and (b) packet loss rate

throughput from 1 Mbps to 19 Mbps as consumers' amount increases from 10 to 500. On the contrary, despite a promising start, the traditional NDN framework fails to cope with our framework as we increase the consumers to 500. As a result, the IC-SDN system maintains a well-balanced performance between high throughput and scalability as the consumers request multiple contents to the network simultaneously. The centralized controller acknowledges these requests from different consumers and installs necessary flows so that these consumers receive those contents properly.

2) *Flow Installation Analysis*: In the traditional SDN-based scenario, execution or installation efficiency of flow messages determines the adaptability and effectiveness of the controller in that scenario. To determine the flow processing rate of the proposed CIC-SIoT controller, we obtain the number of total packet counts and divide them with the multiplication of total number of consumers and number of unique contents. We acknowledge the flow installation time of the controller based on the successful content retrieval. We conduct multiple instances of simulation execution on the basis of the number of unique contents requested by the consumers which is again from 10 to 500 consumers. In the previous experiment on throughput evaluation, we consider random amount of contents requested by the consumers. However, in this experiment, we conduct multiple experiments by setting the custom consumer app to request fixed number of unique contents to 100, 200 and 300 per consumer. As soon as the number of requested unique contents are satisfied, we take the output of the flow installation time and compare the generated data between them. Due to the fact that, the traditional NDN does not have the controller (or management) feature, we only consider the IC-SDN scenario to evaluate the available data among the number of unique

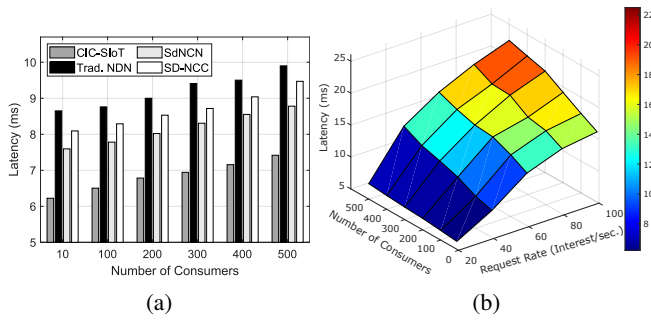


Figure 9: Measurements of latency against varying consumers and request rate.

contents requested by each consumer. Figure 7b shows the flow installation rate for processing different amount of unique contents. In the beginning, the controller takes around 38 ms to install necessary flows that allows producer and the ICN routers to forward those 100 unique contents back to 10 consumer. In case of 200 contents, the controller takes less time under 28 ms and for 300 contents with 10 provides, it takes 10 ms to finish installation of the necessary flow instruction. As soon as, the consumers are increased to 100, the processing time decreases into 10 ms which is similar for 200 and 300 unique contents as well. Finally, we see that, the flow install time seems more or less similar for 200 to 500 consumers. To calculate flow installation rate (FIR) for the IC-SDN controller, we use $FIR = TPC / (NUC \times NoC)$, where number of unique contents is denoted as NUC. The experiment demonstrates that, the flow processing time is higher at the beginning due to the bootstrapping time and acknowledging the topology and discovering the path to the producer. However, as soon as the consumers are increased, the controller starts to process the necessary flows more efficiently which results low flow processing rate and it remains linear for the rest of the experimental time-frame. The increasing number of consumers does not make any negative impact on the flow installation procedure as the results become linear till the end. Additionally, the result also demonstrates that, due to less amount of packet loss, the controller is able to process the increasing amount of contents in a flexible manner while keeping a stable performance. As a result, having a centralized controller in a information-centric environment makes the content retrieval process smoother than the traditional NDN framework.

3) *Caching Efficiency Analysis*: As caching is an important functionality of information-centric network environment, we perform the caching efficiency of the proposed controller implementation by measuring the success or hit ratio. Prior to this experiment, we modify the ICN router in two different ways. Firstly, we enable the caching ability for the ICN routers and collect the number of packets. Afterward, we disable the caching function of the available nodes and execute the same scenario. Figure 8a depicts the average data rate between caching and non-caching prototypes of our IC-SDN framework. There are no significant changes in the overall data rate when the consumers remains at 200, while the framework

achieves a data rate up to 700 Kbps in both scenarios. As we increase the consumers from 300 to 500, the ICN routers start to cache necessary contents whenever possible. The overall caching performance improves compared to the non-caching one. For non-caching scenario, the data request and retrieval processes between 200 consumers and 20 producers have similar performance compared to the caching one. However, as the consumers increases, the data retrieving process from those 20 producers starts to impact the overall performance. On the contrary, in the cache-enabled scenario, consumers directly get the contents from the ICN router without reaching the available producer. Therefore, the limited number of producers does not negatively impact the performance with the availability of cached contents. As a result, the framework achieves a data rate of around 1500 kbps while outperforming the non-caching one that manages up to 1200 kbps data rate.

4) *Packet Loss Analysis*: In this section we calculate rate of packet loss from consumer 10 to 500 with traditional ICN and our proposed CIC-SIoT solution. The technical specification of testbed and simulator configuration is same as throughput. However, in this experiment we calculate the number of lost packet between our IC-SDN implementation and the traditional NDN implementation which is shown in Figure 8b. We denote total transmitted packet as TT and total received packet as TR. Therefore, we use $PLR = (TT - TR) / TT$ to calculate the average packet loss. Compared to the above-mentioned experiments, here we normalize the results within 0% to 0.1%. The traditional NDN system showcases the packet loss rate between 0% to 0.15% regarding the consumers from 10 to 500. On the contrary, the average packet loss rate of our framework achieves between 0.39% to 0.55%. Note that, packet loss occurs due to the limited PIT size which is defined as 10,000 entries.

D. Result Discussion of Numerical Analysis

In the numerical analysis, we compare the efficiency of the proposed algorithm with traditional NDN designed for MATLAB environment [60]. Besides, we also use SD-NCC [35] and SdNCN [66] to compare the feasibility of our solution in terms of content retrieval latency, communication overhead, reduced overhead rate and bandwidth savings. The topology from 5b is deployed in the numerical experiments. Each experiments are performed 10 times and then we calculate the average of these 10 executions for the final outcome.

1) *Content Retrieval Latency*: The content retrieval latency measures the time interval from when the controller receives a request from a consumer to when the consumer responds after successfully obtaining the desired content. As the number of consumers increases, the volume of requests grows exponentially. Figure 9a illustrates the content retrieval latency comparisons among SdNCN, SD-NCC, traditional NDN, and our proposed solution. As the number of consumers rises from 10 to 500, an estimated 200 to 10,000 requests are generated per second. Our proposed solution outperforms the others, attributed to its efficient shortest path algorithm and flow installation prowess. Consequently, the latency for successful content retrieval remains between 6.2 ms and 7.4 ms. In

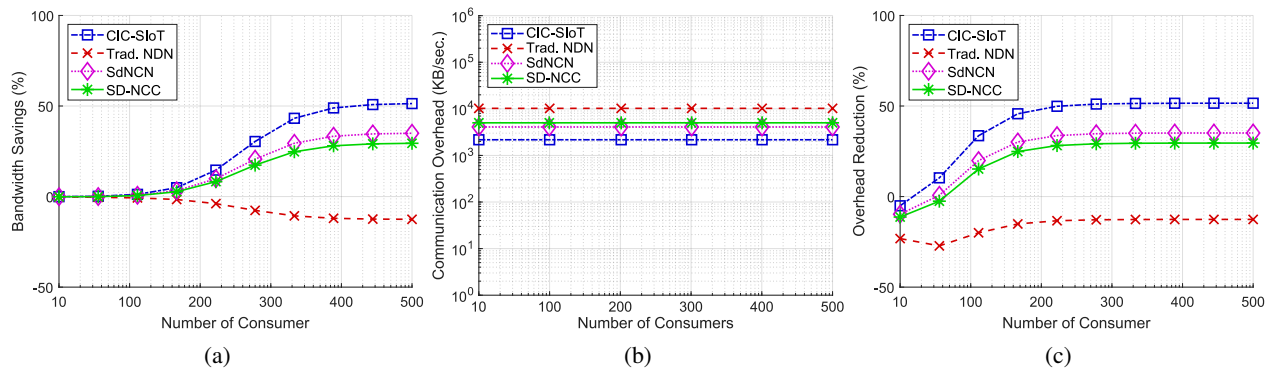


Figure 10: Performance analysis of (a) bandwidth savings, (b) communication overhead, and (c) overhead reduction.

contrast, the latency for traditional NDN ranges from 8.65 ms to 9.9 ms. Furthermore, while SdNCN records a latency slightly better at 8.78 ms, SD-NCC lags at 9.5 ms when accounting for 500 consumers in the topology.

To further evaluate CIC-SIoT's performance under varying workloads, we conduct a comprehensive analysis of content retrieval latency under increasing request rates and consumer numbers. Figure 9b illustrates CIC-SIoT's capability to handle a growing number of consumer requests under different request rates. Starting with 10 consumers, we observe that latency increases from 6.224 ms for 20 requests per second to 16.02 ms for 100 requests per second. As the number of consumers increases to 100, latency rises from 6.504 ms at 20 requests per second to a manageable 17.45 ms at 100 requests per second. This trend remains consistent when we extend the analysis to 500 consumers; latency starts at 7.417 ms for 20 requests per second and increases to 22.48 ms for 100 requests per second. These gradual increases in latency correspond to the increases in request rates, from 20 to 100 requests per second, across consumer groups ranging from 10 to 500. Despite the simultaneous increase in consumer numbers and request rates, the relatively small increase in latency demonstrates CIC-SIoT's effectiveness in scaling and maintaining performance within acceptable limits. This ability to manage higher demands with minimal latency increase is essential for the demanding conditions of IoT environments, showcasing the solution's scalability and stability.

2) *Bandwidth Savings*: The increasing number of control messages causes performance bottlenecks in the network. Hence, bandwidth saving is a critical factor for scalable content distribution in a distributed hierarchical network. In the figure 10a, we evaluate the bandwidth saving capability in terms of how these solutions fare when content dissemination on the disjoint path's link. Here the disjoint path refers to a particular situation where the number of consumers mismatches with the topology density. Within 10 to 100 consumers, there are no spectacular changes in bandwidth compensation. When we increase the number of consumers to 200, the proposed solution restricts the bandwidth usage significantly up to 20% to 50%. The proposed solution achieves approximately 15% and 40% more than 30% of SdNCN and 15% of SD-NCC. The traditional NDN fails to restore bandwidths as the number of consumers increases.

3) *Communication Overhead*: The average communication overhead is another crucial metric determining the controller's efficiency in processing the control messages when the number of consumers increases. The performance comparison of average and reduced communication overhead throughout the ICN nodes are depicted in Figure 10b and Figure 10c. Besides, the proposed solution's average overhead remains lower than the while we also notice the reduced overhead stays within a range of 41% to 52%. The stable overhead result also validates the effective exchange of flow messages between the controller and the ICN router. The controller detects the inactive ICN nodes while there are disjoint paths and takes immediate actions to recover the communication's inactivity.

VI. CONCLUSION AND FUTURE WORK

This paper investigates the effectiveness of an IC-SDN controller within a clean-slate ICN-IoT network to emphasize its role in discovering and distributing desired content through optimal routing. By leveraging the in-network forwarding and caching capabilities of ICN routers, the proposed controller improves content transmission between producers and consumers. To enhance inter-layer communication, we suggest modifying TLV entries in existing interest and data packets to create request and response packets. This modification facilitates scalable communication between nodes in the data layer and the controller in the control layer. Simulation studies and numerical analyses demonstrate the model's efficiency, showing reductions in packet delay, bandwidth usage, and communication overhead, while simultaneously improving caching efficiency and throughput. Future research will explore the deployment of multiple hierarchical IC-SDN controllers within the ICN-IoT paradigm to further enhance content delivery and caching in scenarios such as blockchain and metaverse.

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