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Editorial

Recent Advances in Information-Centric Networks (ICNs)

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The great success of the Internet has been essentially based on the simplicity and versatility of its TCP/IP architecture, which imposes almost no restrictions on either the underlying network technology or on the data being transmitted. In essence, applications built on top of TCP/IP are provided with a point-to-point channel that can be used to transmit arbitrary information.

This approach has served quite satisfactorily for many years, but it no longer suits some of the new communication paradigms currently being used on the Internet [1]. Nowadays, most Internet applications are no longer interested in using a point-to-point channel to exchange traffic between two endpoints. In contrast, what they really want is to access information that is available in the other network nodes. Information-centric networks (ICNs) offer a service where users can directly obtain pieces of information, regardless of their location. This service is more suited to current network uses and to support the highly dynamic nature of mobile networks. Additionally, the legacy point-to-point communication model can be provided on top of it, if so desired.

Named data networking (NDN) is an implementation of ICN that has emerged as a promising candidate for future Internet architecture. In contrast to traditional networking protocols, NDN focuses on the content itself, rather than on its location. NDN enables name-based routing and location-independent data retrieval [2].

This Special Issue, titled "Recent Advances in Information-Centric Networks (ICNs)", aims to highlight and to present recent advances about different problems related to using information-centric network architecture. It contains nine high-quality research papers and one review paper. As usual, the *Future Internet* journal standards required that all the submitted manuscripts went through a rigorous peer-review process.

In the following, we will use the authors' own words to avoid misinterpretation and to provide a more accurate presentation of the contributions of each paper.

The work by Dang and Han (contribution 1), titled "An In-Network Cooperative Storage Schema Based on Neighbor Offloading in a Programmable Data Plane", was the first published paper in this Special Issue. Numerous studies have been conducted on distributed storage in academia and industry, but most storage systems are constructed at the application layer. As a result of the recent development of programmable network technology, solutions have been developed that use in-network computing to offload part of the storage function into the network [3]. This paper proposes the realization of data storage in the forwarding process and the cooperative offloading of the data beyond the local storage capacity to neighboring storage nodes. The proposed solution consists of dynamically splitting traffic among selected neighbor nodes to sequentially amortize excess traffic. The neighbor selection mechanism is based on the Local Name Mapping and Resolution System, in which the node weights are computed through combining the link bandwidth and the node storage capability and determining whether to split traffic via comparing normalized weight values with thresholds. Evaluation shows that the proposed schema is more efficient compared with end-to-end transmission and ECMP in terms of bandwidth usage and transfer time.

In the second contribution, titled "Controlling the Trade-Off between Resource Efficiency and User Satisfaction in NDNs Based on Naïve Bayes Data Classification and

Lagrange Method", Herouala et al. address the trade-offs between resource efficiency and user satisfaction in the limited environments of named data networks (NDNs). The authors propose a strategy, named RADC (resource allocation-based data classification), which aims to manage such trade-offs through controlling the fairness index of the system. As indicated in the title, the method uses a machine learning technique based on multinomial naïve Bayes to classify the received contents, together with an adaptive resource allocation strategy based on the Lagrange method. Simulation experiments confirm the potential usefulness of the strategy to manage the trade-off between efficiency and user satisfaction.

One of the most important components in NDN is the cache strategy, since it improves bandwidth usage, server load, and service time [4]. Yovita et al. address this issue in the third contribution, titled "Weighted-CAPIC Caching Algorithm for Priority Traffic in Named Data Network". They propose the Weighted-CAPIC caching algorithm to improve the priority class performance, through adjusting different weights for every content class in addition to considering the variation of the content in providing a cache portion in the NDN router, without having to coordinate with other routers. The work shows that the proposed caching algorithm provides a higher cache hit ratio for both the priority class and the whole system.

Another work related to cache issues is presented in the paper by Hou et al. titled "Intelligent Caching with Graph Neural Network-Based Deep Reinforcement Learning on SDN-Based ICN" (contribution 10), the last paper to be accepted and published. The work focuses on enhancing cache performance through maximizing the cache hit ratio in software-defined networking (SDN), that is, a context where the ICN offers flexibility, scalability, and efficient resource management [5]. The authors propose a statistical model that generates users' content preferences, incorporating key elements observed in real-world scenarios. Furthermore, they introduce a graph neural network–double deep Q-network (GNN-DDQN) agent to make caching decisions for each node based on the user request history. Simulation results demonstrate that this caching strategy achieves a cache hit ratio significantly higher than the state-of-the-art policy.

The Internet of Vehicles (IoV) is also a promising research area in the field of the Internet of Things [6]. Advances in ICN, edge computing (EC), and artificial intelligence (AI) will transform and help to realize the Intelligent Internet of Vehicles (IIoV). In this context, in contribution 4, Musa et al. provide us with a comprehensive review of utilizing intelligence in EC and ICN to address current challenges in their application to the IIoV. In particular, they focus on intelligent edge computing and networking, offloading, intelligent mobility-aware caching and forwarding, and overall network performance. Furthermore, they discuss potential solutions and highlight potential research directions.

Despite the large amount of works published in the literature about different implementations of NDN architecture, there are few NDN implementations in real networks [7]. Contribution 5 by Gameiro et al., titled "Insights from the Experimentation of Named Data Networks in Mobile Wireless Environment", evaluates the performance of an NDN-based implementation in a mobile wireless network, as part of a smart city infrastructure. This work is especially interesting since ICN has been considered an alternative for overcoming the drawbacks of host-centric architectures when applied to mobile Internet of Things (IoT) networks. Such drawbacks are the frequent topology changes and intermittent connectivity caused by the mobility of the network nodes. The implementation is evaluated in three scenarios, and the results show that the implementation works properly, also deriving insights about correct NDN parameterization.

Contribution 6 brings us another interesting area of application for NDN architecture: satellite communications using LEO constellations with inter-satellite links (ISLs). At present, it is not clear which will be the networking design of these large constellations of LEO satellites, but the idea of using NDN in them is gradually gaining attention since this architecture is especially convenient for highly dynamic network environments [8,9]. Its strongest advantage over IP is mobility management, which is one of the biggest challenges of LEO constellations, given the high orbital speed of these satellites.

Among other native facilities, such as inbuilt security, NDN readily supports the mobility of clients, thus helping to overcome one of the main problems raised in LEO satellite networks. In this work, Iglesias-Sanuy et al. propose a new location-based forwarding strategy for LEO satellite networks that takes advantage of the knowledge of the relative position of the satellites and the grid structure formed by the ISLs. Forwarding at each node is performed using only local information (node and destination locations), without the need of interchanging information between nodes, as is the case with conventional routing protocols. Simulation experiments show that the proposed forwarding strategy is a good candidate to promote the efficient and effective future use of NDN architecture in LEO satellite networks.

Contribution 7, by Xu et al., is closely related to the previous paper. In this work, a novel multipath transmission scheme for NDN is presented, designing a path management mechanism, including path selection and path switching, that can determine the initial path based on historical transmission information and switch to other optimal paths according to the congestion degree during transmission. The experimental results show that the proposed method can improve the average throughput and reduce the average flow completion time and the average chunk completion time.

As the routers in the ICN network can cache the content, there are multiple replicas of a given content in the network. So, when a user requests some content, it is very important to find and select a suitable replica node to improve the user download rate and network throughput, which has been studied by many researchers [10,11]. Contribution 8 by Wang et al. addresses this issue and proposes a replica-selection algorithm to reduce the transmission completion time. The algorithm estimates the transmission completion time of different replica nodes and selects the smallest one. When no replica is found, the nearest-replica algorithm will be used, and so the traffic in the core network will not increase. Experiments show that the algorithm effectively improves the user's download rate and edge node throughput, reduces download rate fluctuations and user download delay, and improves fairness.

Another important issue related to NDN is security. The security features of the NDN design are intrinsic and require signatures to be used in data packets [12]. Producers are responsible for digitally signing all data they create, which enables consumers to validate the authenticity of the retrieved information. Additionally, any NDN node can store data, and consumers can receive data packets from any source. The NDN architecture relies on several security components to ensure data security [13]. But this data verification process may cause significant delays, especially in mobile and vehicular networks. This aspect makes it unsuitable for time-critical and sensitive applications such as the sharing of safety messages. This problem is addressed in contribution 9, where Benmoussa et al. propose NDN-BDA, a blockchain-based decentralized mechanism that enables local data verification while providing a secure authentication mechanism for producer vehicles. By using blockchain, a novel proposal in this field, there is no need for centralized authorities, thereby reducing associated overhead. NDN-BDA was thoroughly evaluated for efficiency against various attacks, which makes it a promising solution to provide a faster and more efficient data authenticity mechanism for NDN-based vehicular networks.

List of Contributions

1. Dang, S.; Han, R. An In-Network Cooperative Storage Schema Based on Neighbor Offloading in a Programmable Data Plane. *Future Internet* **2022**, *14*, 18. https://doi.org/10.3390/fi14010018.
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