Research Efforts on Information-Centric Networking

Hassine Moungla

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Hassine Moungla, *Université de Paris*, LIPADE, F-75006 Paris, France (hassine.moungla@u-paris.fr)

I. Introduction

In the coming decade, there will be tens of billions of connected devices such as sensors, smartphones, cars, and data centers [1], [2]. These connected devices with sensing and decision making capabilities are usually small in size and potentially mobile. This ecosystem makes up the Internet of Things (IoT) [3] that can be deployed with sensing and intelligence capabilities so that these things can not only communicate, but also collect data, negotiate, collaborate, and exchange the collected values.

On the other hand, the current Internet model was developed many decades ago to allow connectivity between specific end-points or devices. Using unique *Internet Protocol* (IP) addresses, most Internet communication happens between a client and a well-known server based on addresses. However, the user's needs have since changed, where they are more related to content sharing rather than the connectivity [4]–[6]. The Peer-to-peer model is one example which primarily aims at content sharing and not on connectivity to a specific server. Nonetheless, communication is still among specific devices sharing the content. Moreover, this device or host-centric model lacks mobility and security as part of its design. Hence, various add-ons and patches have been developed to support them [7], [8]. This makes the model and the system more complex and can impact communication performance.

Information-Centric Networking (ICN) [9] has been proposed as a new architecture for the future Internet, addressing many issues in the current IP-based networks, such as routing process, scalability issue, and content sharing performance. ICN integrates all network functionalities around the name of content rather than the address of the network, in a way to ensure efficient data dissemination and access [10].

Formerly, different concepts such as *Peer-to-Peer* (P2P) and *Content Distribution Network* (CDN) have been developed to improve the content sharing and distribution in the Internet [11]. However, ICN in contrast to P2P and CDN, is a standardized protocol that works at the network layer. P2P is an application-specific protocol, whereas CDN is a proprietary solution working at the application layer. Moreover, P2P content is delivered from end-users, while in CDN proprietary infrastructure is used. However, ICN content can be delivered from the network infrastructure itself. This redesign from "*where* the content is located" to "*what* is the content" will improve the network performance, facilitate the content retrieval and replication using in-network content caching, and support native multicast delivery & mobility [12]. ICN can be used as a communication enabler in different domain-specific networks such as Internet of Things [13]–[16], vehicular networks [17], [18], 5G networks [19], edge computing [20], etc.

Many research works have focused on different ICN functionalities such as naming, forwarding, in-network caching, mobility, and security. In the following sections, we highlight the achieved research by LIPADE.

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II. Content Naming

The content name is the key element in ICN [21], which uniquely identifies the content itself. It should be compact, persistent, and be able to validate the content. The used naming scheme must be scalable and should allow name aggregation.

Works in [22], [23] designed a hybrid multilayer naming scheme with multi-component hierarchical and attribute-value components for a data-centric Internet of Things. The proposed scheme targets smart IoT applications and provides built-in scalability, efficient routing, and security features. The authors incorporated a variable-length encoding method, with a prefix-labeling scheme in order to describe hierarchical location names with various embedded semantic functionalities. Moreover, the scheme supports fast local IoT communication using Name-to-Code translation concept, as well as multi-source content retrieval through in-network function

Work in [24] targeted the naming aspect in vehicular named data networks and proposed a Name-to-Hash Encoding scheme. The idea consists of hashing each name components separately to a fixed length, then perform a heuristic Wu-Manber-like algorithm lookup process. The former process enhances the NDN to consume less memory compared to hierarchical names, the latter process provides a fast lookup time.

III. Forwarding Scheme

The use of names to identify the content introduces name-based routing to discover and deliver the content to the requester [25]. Due to the receiver-driven design, a consumer triggers a request asking for content by specifying its name. The discovery process starts searching for the content based only on the name. The request is forwarded hop-by-hop using a forwarding/routing table until it reaches the original or a replica node that has the requested content, after which the content is delivered to the requester.

Work in [26] proposed a group-based subscription architecture, which enables not only a seamless publisher-subscriber model, but also authentication, access control, and group management features, without modifying ICN principles. Compared to traditional pull-based subscription, this work is able to achieve lesser control overhead, with added security and privacy features.

Work in [27] proposed a Link Quality-based Congestion Control (LQCC) scheme for Named Data Networks in order to avoid congestion in the network and achieve an efficient data delivery. The authors defined different dynamic metrics related to NDN communication. These metrics, along with other metrics such as link utilization, cache store, and the mobility impact, are used to select the optimal and stable path that can be used to forward the interest and deliver that data without facing any congestion issues.

Work in [28] presented a Collaborative Multiple Metric interface ranking scheme (CM^2) for Named Data Networks. In contrast to the existing interface ranking schemes, CM^2 aims to combine multiple metrics with different objectives and applies a decision-making function to rank each interface. This work also introduced three forwarding modes based on the number of used forwarding interfaces, and a one-hop triggered collaborative mechanism to measure metric used in CM^2.

IV. Content Caching

As the content names are location-independent and each data packet is self-consistent, in-network caching [29] can be applied during ICN communication. Each ICN node can cache the content, and serve it for future requests. Caching improves network performance by reducing the delay and facilitating content retrieval. However, deciding what kind of content should be cached in ICN involves treating content based on various metrics including popularity and freshness.

Work in [30] proposed a hybrid cache placement scheme wherein we designed a hybrid cache model with a distributed architecture. The proposed scheme aimed at selecting the optimal placement of content in the content-store by pushing down the popular content toward the edge of the network and keep the less-popular content at the core of the network.

Work in [31] focused on the in-network caching to overcome the content delivery in high mobility environment. Toward this, the authors proposed a proactive caching scheme based on mobility prediction, that aims to select only RSUs in the same direction of consumers to fetch the future requested content and cached them. The authors also introduced LSTM module to predict the mobility movement and select the appropriate RSU as a cache store.

Work in [32] proposed a new caching strategy that aims to minimize the cost of selecting the optimal cache placement in IoT based on traffic classes, taking the cost of data movement from producer to replica nodes, cost of caching in the replica, and the cost of moving the content from replica to consumers into consideration.

Work in [33] proposed a QoS-aware Cache Replacement (QCR) policy. QCR assigns to each content a class, and splits the cache store into a set of sub-cache stores. Each sub-cache store handles one class of content. The authors modeled the problem as a Knapsack problem, and proposed a content popularity-diversity replacement policy that aims to select the content with the highest popularity-density to be cached and the lowest density to be evicted. A trade-off between content popularity and its size is taken into consideration to improve network quality of service.

Work in [34] designed **C**ache a**n**d **S**plit (CnS) cache placement scheme. CnS aims at moving the popular content from the provider level towards the edge router closer to consumers while keeping the less-popular content at the core network. CnS is based on splitting the cache responsibility with the suitable neighbor cache-stores by pushing the popular content downstream. We evaluated the proposed scheme in large-scale topology and compared it with other strategies.

Work in [35] proposed an Energy-aware caching placement scheme (EaCP) strategy in order to improve the energy efficiency of IoT-based ICN networks. EaCP tends to balance the caching cost and the transmission cost in order to achieve a better content placement position. To doing so, we considered content transmission and caching energy, the node position, and content popularity. EaCP algorithm aims to achieve the optimal placement setting in a distributed fashion.

Work in [36] targeted the advantages of using ICN concept in vehicular networks. Notably, the authors focused on the in-network caching to enhance the data dissemination and delivery. Hence, they reviewed the existing caching placement strategies and replacement policies, and provided a comparative study of different strategies showing the effectiveness of ICN caching.

V. Mobility

From ICN perspective [37], the content is independent from its original location, and only the desirable content name is used to discover and forward it back to the consumer. When a node moves from a network to another, it can re-issue any unsatisfied requests, and the producer replies with the requested data without any need to request a new address during the movement [38].

Work in [39] designed a producer mobility architecture based on the Label naming scheme, namely LbPM. The authors used this naming scheme in order to provide location-free producer mobility without changing the location-based hierarchical names. Without exploring extra resources or designing a complex protocol, LbPM exploited the naming feature that is mainly the fundamental building block of ICN.

VI. Security

ICN emphasis content-based security [40], [41], where security mechanisms are applied to content itself rather than the communication process. Different trust models have been developed based on network services. Also, each data packet is self-authenticating based on the original content security-related information (e.g., the publisher's public/secret keys and signature) [42].

Work in [43] presented and discussed a variety of access control mechanisms in NDN. The authors described the paradigm shift from session-based security to content-based security along with different cryptographic algorithms, security protocols, and introduction to access control. They also presented existing NDN-based access control mechanisms and classified them into different categories. Finally, they presented and identified research gaps and challenges that may be considered by the research community when designing efficient access control solutions.

Work in [44] presented a state-of-art of existing VANET attacks and how NDN can deal with them. The authors classified these attacks based on NDN perspective. Furthermore, they defined various challenges and issues faced by NDN-based VANET and highlight future research directions that should be addressed by the research community.

Work in [45], [46] explored the integration of Blockchain technology in Vehicular Named Data Network to secure the communication plane, data delivery, and content caching at the network level rather than the application. In particular, the authors proposed a reputation-based Blockchain scheme in order to enforce the trust between vehicles, secure both the Interest forwarding process and data forwarding plane, and securely ensure anonymous data delivery. Besides, the proposed scheme can be integrated to enforce content copyright and preserve data privacy when applying caching in uncontrolled cache-stores.

VII. What's Next?

Despite the existing ICN solutions proposed in the literature, there are still improvements in the area of ICN applications and challenges to address. In the following, we list both short and long-term perspectives that can give potential enhancements to our studies and future research directions.

The short-term improvements of our work are related to the evaluation and deployment in real-world scenarios. Deployment in testbed running native NDN protocol is extremely required to evaluate the real performance of NDN. The use of a network simulator or NDN on top of IP limits the performance of the proposed solutions to the performance of the underlaying protocol (e.g., TCP or UDP). The use of Raspberry Pi network running native NDN protocol is a suitable fashion to achieve that. Similarly, the deployment cost is another metric to evaluate. For instance, the use of secure communication protocol or distributed caching schemes may have an impact on resource management and energy consumption.

Concerning the long-term perspectives, the proposed ICN caching scheme can be developed from a context-aware point-of-view. Only by using the content naming and some semantic attribute attached with the content, the ICN caching plane decides whether to cache the content or not. Advanced deep learning-based prediction mechanisms (e.g., reinforcement learning) can also be adapted to predict the content popularity, and hence decide the content cache placement and replacement. Finally, a comprehensive study is required to decide if a network needs to migrate to native ICN protocol or using ICN on top IP protocol. Both technical and economical factors need to be studied.

References

[1] C. Boucetta, B. Nour *et al.*, "A Latin Rectangles-based TSCH Scheduling and Interference Mitigation Design," *Computer Networks*, vol. 197, p. 108275, 2021, iF: 3.111, Q1.

[2] C. Boucetta, B. Nour *et al.*, "QoS in IoT Networks based on Link Quality Prediction," in *IEEE International Conference on Communications (ICC)*. Montreal, Canada: IEEE, Jun 2021, pp. 1–6.

[3] M. Laroui, B. Nour *et al.*, "Edge and Fog Computing for IoT: A Survey on Current Research Activities & Future Directions," *Computer Communications*, vol. 180, pp. 210–231, 2021, iF: 3.167, Q1.

[4] J. Choi, J. Han *et al.*, "A survey on content-oriented networking for efficient content delivery," *IEEE Communications Magazine*, vol. 49, no. 3, 2011.

[5] B. Nour, S. Mastorakis *et al.*, "Whispering: Joint Service Offloading and Computation Reuse in Cloud-Edge Networks," in *IEEE International Conference on Communications (ICC)*. Montreal, Canada: IEEE, Jun 2021, pp. 1–6.

[6] Z. Bellal, B. Nour *et al.*, "CoxNet: A Computation Reuse Architecture at the Edge," *IEEE Transactions on Green Communications and Networking*, vol. 5, no. 2, pp. 765–777, 2021.

[7] B. Nour and S. Cherkaoui, "How Far Can We Go in Compute-less Networking: Computation Correctness and Accuracy," *arXiv 2103.15924*, 2021.

[8] B. Nour and S. Cherkaoui, "A Network-based Compute Reuse Architecture for IoT Applications," *arXiv 2104.03818*, 2021.

[9] G. Xylomenos, C. N. Ververidis *et al.*, "A survey of information-centric networking research," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 1024–1049, 2014.

[10] B. Nour, H. Moungla *et al.*, "Editorial: Information-Centric Network enabler communication for Internet of Things," *Future Generation Computer Systems*, vol. 114, pp. 629–630, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167739X20326893

[11] A. Passarella, "A survey on content-centric technologies for the current Internet: CDN and P2P solutions," *Computer Communications*, vol. 35, no. 1, pp. 1–32, 2012.

[12] B. Nour, F. Li *et al.*, "Coexistence of ICN and IP Networks: An NFV as a Service Approach," in *IEEE Global Communications Conference (GLOBECOM)*, Waikoloa, HI, USA, Dec 2019, pp. 1–6.

[13] B. Nour, K. Sharif *et al.*, "A Survey of Internet of Things Communication using ICN: A Use Case Perspective," *Computer Communications*, vol. 142-143, pp. 95–123, Jun 2019.

[14] B. Nour, K. Sharif *et al.*, "A Distributed ICN-based IoT Network Architecture: An Ambient Assisted Living Application Case Study," in *IEEE Global Communications Conference (GLOBECOM)*, Singapore, Dec 2017, pp. 1–6.

[15] B. Nour, K. Sharif *et al.*, "NNCP: A Named Data Network Control Protocol for IoT Applications," in *IEEE Conference on Standards for Communications and Networking (CSCN)*, Paris, France, Oct 2018, pp. 1–6.

[16] H. Khelifi, S. Luo *et al.*, "Bringing Deep Learning at The Edge of Information-Centric Internet of Things," *IEEE Communications Letters*, vol. 23, no. 1, pp. 52–55, Jan 2019.

[17] H. Khelifi, S. Luo *et al.*, "Named Data Networking in Vehicular Ad hoc Networks: State-of-the-Art and Challenges," *IEEE Communications Surveys and Tutorials*, vol. 22, no. 1, pp. 320–351, 2020.

[18] H. Khelifi, S. Luo *et al.*, "Vehicular Networks in the Eyes of Future Internet Architectures," in *Managing Resources for Futuristic Wireless Networks*, 2021, pp. 70–97.

[19] O. Serhane, K. Yahyaoui *et al.*, "A Survey of ICN Content Naming and In-network Caching in 5G and Beyond Networks," *IEEE Internet of Things Journal*, 2020.

[20] B. Nour, S. Mastorakis *et al.*, "Compute-Less Networking: Perspectives, Challenges, and Opportunities," *IEEE Network*, vol. 34, no. 6, pp. 259–265, 2020.

[21] S. S. Adhatarao, J. Chen *et al.*, "Comparison of naming schema in ICN," in *IEEE International Symposium on Local and Metropolitan Area Networks (LANMAN)*, 2016, pp. 1–6.

[22] B. Nour, K. Sharif *et al.*, "M2HAV: A Standardized ICN Naming Scheme for Wireless Devices in Internet of Things," in *International Conference Wireless Algorithms, Systems, and Applications (WASA)*, Guilin, China, Jun 2017, pp. 289–301.

[23] B. Nour, K. Sharif *et al.*, "A Unified Hybrid Information-Centric Naming Scheme for IoT Applications," *Computer Communications*, vol. 150, pp. 103–114, Nov 2019.

[24] H. Khelifi, S. Luo *et al.*, "A Name-to-Hash Encoding Scheme for Vehicular Named Data Networks," in *International Wireless Communications & Mobile Computing Conference (IWCMC)*, Tangier, Morocco, June 2019, pp. 603–608.

[25] M. Amadeo, C. Campolo *et al.*, "Forwarding strategies in named data wireless ad hoc networks: Design and evaluation," *Journal of Network and Computer Applications*, vol. 50, pp. 148–158, 2015.

[26] B. Nour, K. Sharif *et al.*, "ICN Publisher-Subscriber Models: Challenges and Group-based Communication," *IEEE Network*, vol. 33, no. 6, pp. 156–163, 2019.

[27] H. Khelifi, S. Luo *et al.*, "LQCC: A Link Quality-based Congestion Control Scheme in Named Data Networks," in *IEEE Wireless Communications and Networking Conference (WCNC)*, Marrakech, Morocco, Apr 2019.

[28] B. Nour, H. Khelifi *et al.*, "A Collaborative Multi-Metric Interface Ranking Scheme for Named Data Networks," in *International Wireless Communications & Mobile Computing Conference (IWCMC)*, Limassol, Cyprus, Jun 2020, pp. 2088–2093.

[29] I. Abdullahi, S. Arif *et al.*, "Survey on caching approaches in Information Centric Networking," *Journal of Network and Computer Applications*, vol. 56, pp. 48–59, 2015.

[30] B. Nour, H. Khelifi *et al.*, "A Distributed Cache Placement Scheme for Large-Scale ICN Networks," *IEEE Network*, vol. 34, no. 6, pp. 126–132, 2020.

[31] H. Khelifi, S. Luo *et al.*, "An Optimized Proactive Caching Scheme based on Mobility Prediction for Vehicular Networks," in *IEEE Global Communications Conference (GLOBECOM)*, Abu Dhabi, United Arab Emirates, Dec 2018, pp. 1–6, Best Paper Award.

[32] B. Nour, K. Sharif *et al.*, "NCP: A Near ICN Cache Placement Scheme for IoT-based Traffic Class," in *IEEE Global Communications Conference (GLOBECOM)*, Abu Dhabi, United Arab Emirates, Dec 2018, pp. 1–6, IEEE Student Travel Grant.

[33] H. Khelifi, S. Luo *et al.*, "A QoS-aware Cache Replacement Policy for Vehicular Named Data Networks," in *IEEE Global Communications Conference (GLOBECOM)*, Waikoloa, HI, USA, Dec 2019, pp. 1–6.

[44] H. Khelifi, S. Luo *et al.*, "Security and Privacy Issues in Vehicular Named Data Networks: An Overview," *Mobile Information Systems*, vol. 2018, pp. 1–11, Sep 2018.

[34] O. Serhane, K. Yahyaoui *et al.*, "CnS: A Cache and Split Scheme for 5G-enabled ICN Networks," in *IEEE International Conference on Communications (ICC)*, Dublin, Ireland, Jun 2020, pp. 1–6.

[35] O. Serhane, K. Yahyaoui *et al.*, "Energy-aware Cache Placement Scheme for IoT-based ICN Networks," in *IEEE International Conference on Communications (ICC)*. Montreal, Canada: IEEE, Jun 2021, pp. 1–6.

[36] H. Khelifi, S. Luo *et al.*, "In-Network Caching in ICN-based Vehicular Networks: Effectiveness & Performance Evaluation," in *IEEE International Conference on Communications (ICC)*, Dublin, Ireland, Jun 2020, pp. 1–6.

[37] G. Tyson, N. Sastry *et al.*, "A survey of mobility in information-centric networks: Challenges and research directions," in *ACM Workshop on Emerging Name-Oriented Mobile Networking Design-Architecture, Algorithms, and Applications*, 2012, pp. 1–6.

[38] B. Nour, H. I. Khedher *et al.*, "Internet of Things Mobility over Information-Centric/Named-Data Networking," *IEEE Internet Computing*, vol. 24, no. 1, pp. 14–24, Jan 2020.

[39] O. Serhane, K. Yahyaoui *et al.*, "A Label-based Producer Mobility Support in 5G-enabled ICN Networks," in *International Wireless Communications & Mobile Computing Conference (IWCMC)*, Limassol, Cyprus, Jun 2020, pp. 2094–2099.

[40] Z. Zhang, Y. Yu *et al.*, "An Overview of Security Support in Named Data Networking," *IEEE Communications Magazine*, vol. 56, no. 11, pp. 62–68, 2018.

[41] B. Nour, S. Mastorakis *et al.*, "Information-Centric Networking in Wireless Environments: Security Risks and Challenges," *IEEE Wireless Communications*, vol. 28, no. 2, pp. 121–127, 2021, iF: 11.979, Q1.

[42] B. Nour, K. Sharif *et al.*, "Security and Privacy Challenges in Information Centric Wireless IoT Networks," *IEEE Security & Privacy*, vol. 18, no. 2, pp. 35–45, March 2020.

[43] B. Nour, H. Khelifi *et al.*, "Access Control Mechanisms in Named Data Networks: A Comprehensive Survey," *ACM Computing Surveys*, 2020.

[45] H. Khelifi, S. Luo *et al.*, "Reputation-based Blockchain for Secure NDN Caching in Vehicular Networks," in *IEEE Conference on Standards for Communications and Networking (CSCN)*, Paris, France, Oct 2018, pp. 1–6.

[46] H. Khelifi, S. Luo *et al.*, "A Blockchain-based Architecture for Secure Vehicular Named Data Networks," *Computers & Electrical Engineering*, vol. 86, p. 106715, 2020.