Torres *et al. Journal of Internet Services and Applications* (2019) 10:20
https://doi.org/10.1186/s13174-019-0119-6

Journal of Internet Services and Applications

RESEARCH Open Access

Evaluating CRoS-NDN: a comparative performance analysis of a controller-based routing scheme for named-data networking

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Abstract

The huge amount of content names available in Named-Data Networking (NDN) challenges both the required routing table size and the techniques for locating and forwarding information. Content copies and content mobility exacerbate the scalability challenge to reach content in the new locations. We present and analyze the performance of a proposed Controller-based Routing Scheme, named CRoS-NDN, which preserves NDN features using the same interest and data packets. CRoS-NDN supports content mobility and provides fast content recovery from copies that do not belong to the consumer-producer path because it splits identity from location without incurring FIB size explosion or supposing prefix aggregation. It provides features similar to Content Distribution Networks (CDN) in NDN, and improves the routing efficiency. We compare our proposal with similar routing protocols and derive analytical expressions for lower-bound efficiency and upper-bound latency. We also conduct extensive simulations to evaluate results in data delivery efficiency and delay. The results show the robust behavior of the proposed scheme achieving the best efficiency and delay performance for a wide range of scenarios. Furthermore, CRoS-NDN results in low use of processing time and memory for a growing number of prefixes.

Keywords: Named-data, Content-centric, Information-centric, Networking, Software-defined, Routing protocols

1 Introduction

Named-Data Networking (NDN) applications refer directly to content names, instead of host network identifiers for communication [1]. In this new paradigm, both host mobility/multihoming and content mobility/multihoming do not concern applications because the NDN-network layer focuses on unique network-visible names that identify content. It forwards two types of packets: interest and data packets.

The interest packet is issued by the consumer, it contains the name of the requested content and routers forward the interest towards the closest known copy for this content. Each router, on the way from the consumer to the content copy, keeps a registry of the interest packet, such that the data packet containing the desired content finds the return path back to the consumer. NDN ensures efficient communication, load balancing, energy efficiency, and flow control through popular content storage and data packet replies from any cached copy of the content [1–5]. Interest and data packets one-to-one correspondence avoids link congestion due to Distributed Denial-of-Service (DDoS) attacks [6, 7]. Unlike IP Multicast [8], NDN flow control is receiver-oriented and adapts to the link capacity of each individual consumer.

Named-data routers find and deliver content based on its name and, therefore, NDN routing schemes announce named-data prefixes revealing their associated data location. Nonetheless, NDN routing schemes based on conventional routing protocols, such as Open Shortest Path First (OSPF) and Border Gateway Protocol (BGP), suffer from the high number of named-data prefixes. They inherit IP characteristics due to their focus on prefix dissemination and routing. Additionally, with the intention of reaching content copies stored outside their original locations due to mobility, multihoming, and in-network caching, NDN routing schemes announces more routes with less-aggregated prefixes. Consequently, the routing

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schemes must store more routes and exchange more control messages to announce all the addressable contents, which results in high control overhead and possible risk of Forwarding Information Base (FIB) explosion [9]. That risk, often mitigated by suppressing announcements of non-aggregated prefixes, is likely to limit the cache-hit opportunities to copies located along the path from consumer to producer. Nevertheless, caching along the path from consumer to producer requires cache sizes big enough to accommodate frequently accessed contents that last enough time to serve content to repeated requests. This is a technical and economical trade off considering the large amount of available content and the long tail of content popularity distribution [10].

In a previous paper [11], we formally specified the Controller-based Routing Scheme for Named-Data Networking (CRoS-NDN) using the Specification Description Language (SDL) to avoid ambiguity caused by specifications in natural language. We formally validated CRoS-NDN to prove its correctness and also make a CRoS-NDN proof of concepts of proposed features [12]. CRoS-NDN employs the separation of data and control planes in order to consolidate in the controller the information about network topology and content localization. We designed the CRoS-NDN controller to evaluate routes on demand and, then, return this information inside data packets in response to route requests in interest packets issued by routers, which preserves interest and data packets one-to-one correspondence in Named-Data Networking (NDN) communication model. Each router proactively informs the controller about the routing adjacency and reachable prefixes over the information encoded in interest names. Any updates from the routers trigger the controller that facilitates a consolidated view and enables free placement of content without ties between names and localization.

In this paper, we analyze the CRoS-NDN performance and compare the results with other known NDN routing/forwarding schemes. We also introduce the CRoS-NDN Tunnel Extension that reduces the route-request rate perceived by the controller by encapsulating content names with network segment identifiers and thereby reducing the FIB memory required at core routers due to multiple FIB entries aggregation with the common encapsulation prefix. Our evaluation focuses on the communication overhead and the data delivery latency of each scheme for a single administrative domain and one controller, but we also provide insights on extending the scheme to multi-controller and multi-domain scenarios, like the Internet. We present expressions derived from our analysis for lower bounds of the communication efficiency and upper bounds for the latency, worst-case scenarios. We evaluate CRoS-NDN against other protocols for NDN in the ndnSIM simulator and perform extensive simulations and measurements to compare the different approaches. The obtained results demonstrate that CRoS-NDN is robust and shows similar or superior efficiency, concerning the message overhead of data delivery, in most of the scenarios when compared to the evaluated schemes. CRoS-NDN also improves mobility efficiency of content producers. Furthermore, it achieves the CDN requirement of lower delay from consumer to content and results in less messaging overhead.

The rest of this paper is organized as follows. Section 2 discusses the related work, including the main NDN schemes used in the comparative analysis. Section 3 presents the CRoS-NDN proposal. Section 4 analyses the performance of the compared NDN schemes and Section 5 presents the simulation results. Section 6 introduces the CRoS-NDN Tunnel Extension. Finally, Section 7 concludes the paper and discusses future work.

2 Related work

Ghodsi et al. [13] question the Information Centric Network (ICN) concept due to the very long tail of content popularity distribution. It is important to note that popular contents are the ones more frequently requested and a long tail implies the majority of content items have low popularity. They argue that pervasive caching at all routers is worthless for an approach that caches content responses from producer only in routers along the path to reach the consumer and that a single proxy cache would provide the same results. Nevertheless, a single proxy cache cannot mitigate and prevent server load from flash crowd events and Distributed Denial of-Service (DDoS) attacks contrary to NDN. In addition, they argue that locating content copies outside the path to producer requires a location resolution system that operates at the rate given by the ratio of packet speed to the mean object size. We note, however, that the very long tail stands for aggregated measures of content popularity distribution taken for thousands of consumers employing large time windows. On the other hand, individual consumers present a much less flatter tail for popularity distribution measures of content prefixes taken for smaller time windows [14]. Thus, we can envision access routers to cache name-resolution data for local consumers. Moreover, the volume of video traffic dominates the total IP traffic today and keeps growing. We argue that locating content copies outside the path to the producer is worthy and more efficient because video traffic contributes to a lower rate of name resolution requests due to the typically large content size.

Among several other ICN research surveys, many of them [15–22] point to scalability as a major challenge due to the vast size of the content naming space. Our proposed routing scheme addresses the issues of routers memory requirement and the volume of exchanged control messages.

Several existing schemes propose a publish-subscribe architecture [23–25]. However, this approach is vulnerable to denial of service attacks, as it allows more than one data packet per content request, not preserving the flow balance provided by NDN approach. Other schemes focus on the mapping problem of content identifier to location [26–31]. For example, Baid et al. propose a two level indirection scheme that maps named-data prefixes to a reduced set of flat identifiers and, then, maps these identifiers to network addresses [29]. Baid et al. scheme employs a distributed hash table (DHT) to provide this indirection, that way reducing the FIB memory requirement and control messages exchange. Similar to previously cited mapping schemes, however, it does not preserve content names on forwarding decisions. The mapping of content name to location identifiers should i) preserve content name on packet forwarding decisions rather than topology identifiers alone in order to aggregate unanswered requests for the same content, ii) cache response data, iii) reply to requests with local content copy, and iv) invalidate forwarding rules upon timeout of unanswered content requests.

Afanasyev et al. propose to use the Domain Name System (DNS) for mapping and encapsulating data names into a reduced set of network names related to network domains [28], which consequently reduces the memory requirements and capacity needs. Domain Name System (DNS) servers, however, do not know the request originator and, hence, DNS response contains multiple names and routers must execute multiple prefix-based lookups to find the shortest path for each content. The authors also argue that name changes must be avoided due to complex implications on the name-based scheme, as stated before. Zhang et al. propose a tunneling approach that changes content names and inherits the NDN benefits [32]. These two proposals are integrated into CRoS-NDN Tunnel Extension, and can be enabled to provide higher scalability in content location storage and retrieval.

Software Defined Networking (SDN) has been recently proposed as a means to consolidate routing decisions in a centralized controller. Shi et al. propose a data synchronization scheme for NDN that can replicate the controller information [33] and provide redundancy. Gao et al. propose a Scalable Area-based Hierarchical architecture (SAHA) for intra-domain communication to address the control plane scalability problem [34]. Salsamo et al. propose an SDN-based architecture for ICN, using OpenFlow protocol. OpenFlow works on top of the TCP/IP protocol stack to provide remote access to the forwarding plane of a router or switch and, therefore, suffers from the well-known IP restrictions, including, host mobility and multihoming [35].

Farinacci et al. propose the Locator/ID Separation Protocol (LISP), which separates IP addresses into two distinct numbering spaces, Endpoint Identifiers (EIDs) and Routing Locators (RLOCs) [36]. The egress tunnel router (ETR) for a site maps these two numbering spaces. ETR employs RLOCS to encapsulate traffic originated by endpoints and then transport encapsulated packets across the site network infrastructure. In this regard, our CRoS-NDN approach is similar to LISP, using a centralized routing database to answer routing requests, however, CRos-NDN addresses are mapped to content, instead of endpoints. Furthermore, Raad et al. demonstrate that LISP still face challenges at mobility scenarios between different sites [37] resulting from endpoint mobility constraints. Hence, CRoS-NDN content-based approach offers advantages over LISP in mobility scenarios, as there are no constraints to content mobility and content is not tied to a specific endpoint. It is worth noting that the LISP database returns the final router address while the used controller database returns all router IDs in the path along the destination.

Garcia-Luna-Aceves et al. have proposed CCN-RAMP [38] access routers that resolve content names to router anchors and forward packets employing label switching. The packet forwarding solution reduces the size of FIB and PIT tables and their respective lookup times. Nevertheless, the scheme does not take into account content mobility and the message overhead required for updating the resolution table of the access routers. In addition, this Garcia-Luna-Aceves et al. CCN-RAMP scheme loses the flow control benefit of one-to-one balance of interest and data packets per link. Content caching and an effective distribution of contents among neighboring routers becomes a major challenge NDN. Coordinated caching schemes are widely studied to provide a higher cache hit ratio. Mun and Lin have proposed the sharing of Bloom-filter summaries among neighboring routers to reduce the inter-AS traffic [39]. Bastos and Moraes have proposed DIVER [40], a search-and-routing mechanism for Named-Data Networking that uses generalized Bloom filters [41] to explore the network in order to search nearby replicas stored in cache, improving users experience and reducing network load. Majeed et al. have proposed a pre-cache approach for video streams, but this proposal do not take into account the dynamic behavior of the flows [42]. Wang et al. propose a hop-based probabilistic caching that pushes content copies to the network edge by considering the distance from the content source and the mean residence time of content in cache [43]. Aloulou et al. [44] propose a new controller-based, neighborhood content-aware, popularity driven routing tightly coupled with a cooperative caching strategy, named Controller-Based Caching and Forwarding Scheme (CCFS). They also investigate the optimal controller placement for a controller-based NDN forwarding scheme (CCFS) [45]. The gain of these proposals is strongly dependent of the content popularity with no benefit for content with low popularity. In this paper, we do not focus on sophisticate caching schemes. We consider that caching can improve our proposal performance and can be aggregate to our proposition in a future stage of development.

Albry et al. have proposed a SDN-based routing scheme for CCN [46]. Simulation results show that their proposal increases the cache-hit rate, assuming infinity memory size, and provides a reduced number of control messages, when compared with the worse diffusion procedure that does not learn with the received information. In a second paper, Albry et al. implement their proposal for a unique topology with only eleven routers and provides results for a few situations in a unique condition [47]. The two papers do consider the ideal condition of infinity FIB-memory size and they do not compare the obtained results with any other CCN routing protocol. Ascigil et al. [48] propose an On-Demand Routing (ODR) scheme, where routing information of each domain is collected and maintained by a local service of the domain. Their work is similar to our CRoS-NDN proposal that employs the controller to implement the routing service.

We present CRoS-NDN that natively splits content identity from content location, similar to NDN, enabling content mobility and multihoming. We define specific names and procedures for routers and controller efficient communication over NDN. CRoS-NDN preserves NDN features by keeping the named-data packet forwarding scheme of NDN. Our approach reduces control message flooding and router FIB memory requirement by leveraging information such as global network view provided by SDN. These improvements can be achieved by storing in router FIB only active consumed prefixes instead of all published prefixes, which are orders of magnitude more than the actively consumed prefixes [49], and by replacing the oldest added forwarding rules with recent ones. We also believe that on-demand route-request avoids the replication of routing information from controller to routers upon topology change or content mobility. In addition, the routers and the controller may sign the interests for secure provenance and validity, as in Voice-over Content-Centric Network (VoCCN) [50]. Finally, techniques proposed for securing SDN controllers may be leveraged.

We analyze the performance and compare it with the main routing/forwarding schemes used for NDN in the literature: INFORM [51], OSPF Based Routing Protocol for Named Data Networking (OSPFN) [52], Named-Data Link State Routing (NLSR) [53], and Distance-based Content Routing (DCR) protocol [54]. INFORM is an adaptive hop-by-hop forwarding algorithm that discovers routes towards temporary item replicas through exploration in the data plane, which can be exploited later on for subsequent requests for the same objects. OSPFN is an implementation over IP network. It reuses IP OSPF to distribute NDN routing information using opaque Link State Advertisements (LSA). Our work evaluates only pure NDN protocols that are not IP dependent and, therefore, we do not evaluate OSPFN. Named-Data Link State Routing (NLSR) is a producer-oriented approach that avoids flooding procedure. NLSR replaces OSPF periodic flooding of prefix announcements with a hop-by-hop procedure for database synchronization. NLSR has been developed specifically for NDN and, therefore, each NLSR router maintains the full view of the network in a local database called Link State DataBase.

3 Proposed routing scheme: CRoS-NDN

In [12], we proposed, specified, and validated a Controller-based Routing Scheme for Named-Data Networking (CRoS-NDN). CRoS-NDN uses interest and data packets introduced in NDN and leverages the SDN paradigm to avoid control message flooding. Unlike routing schemes based on prefix announcements, CRoS-NDN does not impose hierarchically indexed prefixes tied to location in order to summarize routing information that must fit in the FIB size. In addition, unlike the name resolution[1] approach of the Domain Name System (DNS), CRoS-NDN localization is topology aware. Furthermore, CRoS-NDN improves the mobility efficiency of content and content hosts because our scheme consolidates the routing information for content localization and router adjacencies. Unlike CRoS-NDN consolidation of processing and memory capacity for route-calculation functions in the controller, other name-based content routing approaches require provisioning of routers with processing power capacity and storage space capable to handle peak-utilization of its local control plane operations. However, most of the time, routers run with spare resources in distributed approaches [55].

The key idea of CRoS-NDN is to define specific names and procedures for an efficient communication over NDN of routers and controller, preserving NDN features for named-data packet forwarding. Unlike SDN-based solutions, our proposal forwards only named-data packets and removes the dependency on IP for routers communication while maintaining a consolidated control plane. CRoS-NDN automates configuration management to establish routers and controller communication, thus, avoiding manual provisioning of network routers. Routers pro-actively register network information at the controller and reactively, on an on-demand

[1] We argue that resolution denotes resolving a name to a location and routing denotes establishing paths to locations. NDN does routing to content. Therefore, NDN names point paths to content and not to locations. NDN original proposal does not concern resolution.

basis, request new routes from the controller for locally unknown name prefixes. Pending Interest Table (PIT) of routers keeps track of no-response interests up to their lifetime expiration. PIT expiration is native to NDN, but CRoS-NDN adds specific actions to remove invalid forwarding rules in the FIB upon PIT entries expiration. Furthermore, CRoS-NDN routers update the controller topology view upon failure to reach neighbor routers. Unlike CRoS-NDN, NDN does not have the means for the routing protocol to provide feedback based on PIT expiration.

The CRoS-NDN scheme involves two phases: Bootstrap and Named-Data Routing. The Bootstrap phase monitors the routers to establish the knowledge of the global network topology. The Named-Data Routing phase guarantees the localization and access to the requested content [12]. CRoS-NDN performs Controller Discovery, Hello, and Router Registration procedures in the Bootstrap phase. In the Named-Data Routing phase, it performs the Named-Data Registration, Route Request, and Route Installation procedures. Figure 1 illustrates the interest and data packets sequence in CRoS-NDN. Accordingly, Hello and Controller Discovery procedures start simultaneously at the initialization. The Hello procedure runs periodically. Topology changes detected by Hello, Controller Discovery data, and failure of Route Installation start the Route Registration procedure. Producers start the Named-Data Registration procedure at their access routers to register their available content. Consumers start the Route Request procedure upon FIB miss in routers. Route Request data and Route Installation interests start the Route Installation procedure. The time expiration of interests for Controller Discovery, Route Registration, Named-Data Registration, and Route Requests from routers to controller starts the Controller Discovery procedure.

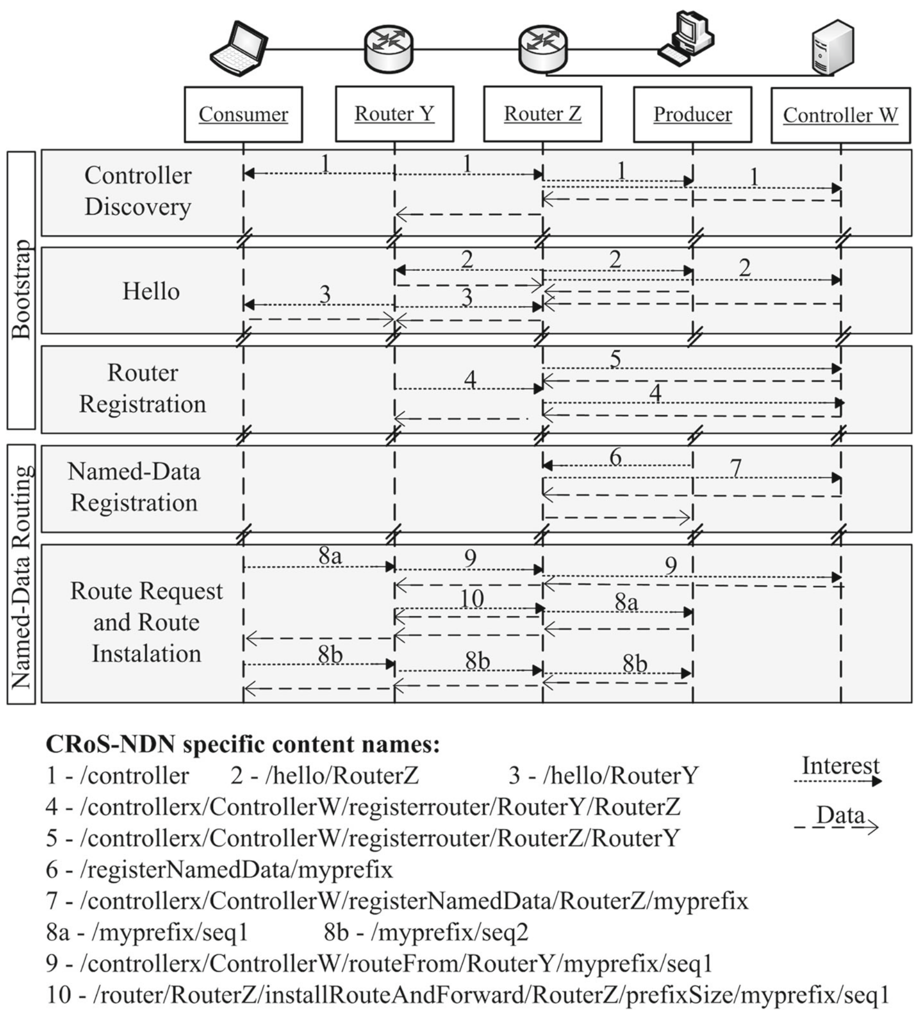


Fig. 1 The Interest/Data time sequence for CRoS-NDN procedures

3.1 Bootstrap phase

Our scheme employs just named-data packets and does not depend on IP addresses and protocols for router and controller communications. Thus, we avoid IP issues related to multihoming and mobility. To this end, CRoS-NDN automates the discovery of router-controller paths, instead of pre-configuring routers with IP controller IP address as typically done in OpenFlow based SDN networks. Routers flood the network to find initially the controller, during the Controller Discovery procedure. Afterwards, the controller discovery only repeats upon no-response time expiration of router to controller interest. Furthermore, cache and interest aggregation reduce the discovery overhead. Therefore, CRoS-NDN wider broadcast domain does not incur additional signaling overhead for controller discovery because our scheme restricts network interest flooding. Each router monitors its one-hop neighbors, using Hello packets, and the router registers any topology change informing router identified adjacencies to the controller, during Router Registration procedure. Routers also register in the controller the locally produced content name prefixes, using the Named-Data Registration procedure. The controller stores the received information from network routers and acquires knowledge of the network topology and that of content location.

3.2 Named-data routing phase

Unlike SDN-based solutions in which each router in the consumer-producer path requests a route from the controller, CRoS-NDN end-to-end route installation charges the controller with only one route request during Route Request procedure. The route-requesting router informs its identifier and the requested content name in the route request sent to the controller. Upon a route request, the controller identifies the requesting router and locates the content producer router. Afterwards, the controller computes the sequence of router identifiers in the path from consumer to producer and answers the route request. Upon the controller answer for the route-request, the router starts the Route Installation procedure, in which the requesting router uses source routing to build a specific interest packet that installs the new FIB entry on each router in the path from consumer to content producer. The route-install interest name encodes the sequence of router identifiers in the calculated path. The interest packet is modified on a hop-by-hop basis by removing the current hop and forwarding the new interest packet ahead. In this paper, we compute the shortest path, although the controller may also be configured to use other routing metrics, for instance, to achieve better overall quality of service [56, 57].

CRoS-NDN preserves NDN id-locator split feature, while existing NDN implementations employ prefix aggregation that ties together the location and identification semantics. This feature of CRoS-NDN facilitates mobility and multihoming. The CRoS-NDN Named-Data Registration procedure provides content-copies reachability at any location. In addition, the Route-Request procedure jointly resolves the content location, determines the shortest path in hop count from consumer to each registered content copy, and chooses the path with the lowest cost. This way, content distribution servers store content copies and register content location in the controller. CRoS-NDN does not change the way NDN routers cache content. The CRoS-NDN Named-Data Registration procedure allows any host to register as a producer for a content prefix. Accordingly, a host registering a cached copy out of the path to producer can be closer to consumer than the original producer, which improves efficiency. An authorized host can decide to register in the controller to serve a content it has cached previously. The controller may block hosts from registering content copies and may require authorization. Host managers may apply specific policies to enforce the registration of copies for specific prefix names caching that content for longer times.

The decision of which content must be registered and when it must be registered is a policy question; each host may have its local policy. A policy, for instance, is to cache and register the content of specific producers, another example of police is to cache and register big content values. The two-extreme polices are cache and register no content or all contents. When the consumer, which can be mobile, requests a content, the access router requests a route from controller. When a producer moves, a content registration update is required. The old access router of the producer removes content registration upon failure response for requests sent to the producer. The access router may monitor the connectivity with the directly attached producers to speed up the process. When a consumer moves, the new access router may need to request a new route from the controller.

Topology changes or content mobility can invalidate FIB router entries. Therefore, unlike SDN-based solutions where the controller pro-actively updates all FIB of routers, upon any change, CRoS-NDN employs data-plane feedback procedure to remove invalid FIB entries only on the routers in which there is a request for content pending in PIT, i.e., in the content path. Interest packets for which there is no matching entry in the Forwarding Information Base (FIB) trigger the Route Request procedure. Interests, which have not been acknowledged with a response, initiate the Pending Interest Table (PIT) entry removal after the interest lifetime expiration. Then, on PIT entry removal, our scheme evicts the associated FIB entries. Actually, upon PIT expiration, the respective FIB entry enters a yellow state. Upon a second PIT expiry for the same FIB entry, the FIB entry enters in a red state.

Upon the next PIT expiry, the scheme removes the FIB entry. In the meantime, upon a successful data delivery for a PIT entry related to this FIB entry, the FIB entry moves to green state. This process avoids the FIB entry removal in core routers, which aggregate packets from many consumers for the same prefix. Consequently, the FIB entry removal moves to the edge/access router of the consumer. In addition to reducing the signaling overhead, CRoS-NDN lessens the requirement for router's FIB memory to the scale of simultaneously consumed prefixes. It reuses FIB memory and replaces old entries with new ones. This is in contrast to supporting all content prefixes available in the network irrespectively of consumer pattern of content requests for different prefixes.

3.3 Multi-controller and multi-domain deployments

CRoS-NDN extension to a multi-controller scenario for deployments in large-scale intra-domain networks can be envisioned as follows. Multiple controllers can share the named-data location storage task and each controller knows a subset of routers, henceforth called zone [58], and paths between routers in its own zone. Each controller must have the topological view of the adjacent zones, so it can calculate the next zone hop to any other zone in the network. The controllers may be organized in a distributed hash table (DHT) using the hash of controller ID as the DHT node identifier, and the hash of named-data prefix as the DHT key. The DHT value is the router ID for the prefix. Key distribution in DHT nodes follows an index rule based on DHT node ID. Rendezvous hashing reduces disruption upon a controller failure or addition [59]. Furthermore, each controller stores a local copy of the information regarding its own zone to reduce sub-optimal name-based routing issues in content name to zone resolution.

CRos-NDN deployment in multi-domain scenarios can be approached in different possible ways. One approach is to employ a hierarchy of controllers with the root administered by an independent organization (similar to ICANN for DNS root servers). Each domain has autonomy on which information to announce to the root controllers. In an alternative approach, domains announce directly to each other the relevant information. The choice of approach will be dictated by the tradeoff between administrative autonomy and the overhead of exchanging information directly with all domains. The evaluation of the efficiency of route request resolution for multi-domain scenarios is out of scope of this paper and will be considered in a future work.

4 Performance analysis

We aim to evaluate and compare the performance of our proposal with the main routing/forwarding schemes used for NDN in the literature. In this section, we derive mathematical expressions for the Data Delivery Efficiency (DDE) lower bound and the Data Delivery Delay (DDD) upper bound. The data delivery efficiency is the ratio of the consumer-received data packets to the number of interest packets sent on each network link. We define data delivery delay as the delay between consumer content request and consumer content reception. Maximum efficiency equal to 1 and minimal delay equal to zero are only achieved when the desired content is cached on consumers. Otherwise, the efficiency decreases and the delay increases with the number of hops traveled to obtain the required data.

As we have mentioned before, the main NDN routing/forwarding schemes are: INFORM [51], OSPF Based Routing Protocol for Named Data Networking (OSPFN) [52], Named-Data Link State Routing (NLSR) [53], and Distance-based Content Routing (DCR) protocol [54]. Unfortunately, we do not have the implementation codes of these protocols and a complete implementation of all these protocols requires unnecessary effort for our aims of performance comparison. Therefore, we implemented simplified versions of these protocols, omitting optimizations and details that do not compromise the performance comparison. We add the term like to signalize our implementation instead of the original proposal.

Instead of the complete implementation of INFORM, we implemented the flooding procedure used by INFORM for exploration and direct forwarding to exploit learned paths. We call this implementation ARP_{Like} because it is similar to the Address Resolution Protocol (ARP) procedure used by IP networks. It employs a consumer-oriented approach that reacts to consumer content requests flooding the network with interests for contents that have unknown forwarding rules, i.e., whenever the incoming interest does not match any FIB entry. Upon content response arrival, *INFORM* router updates its FIB adding a new entry with the content name prefix and directly forwards the subsequent interests with the same prefix.

We do not evaluate OSPFN because it is not a pure NDN protocol, actually, it is an implementation over IP network. Hence, for comparison purpose, instead of implementing OSPFN, we implement a proactive producer-oriented approach to announce content availability that follows Content Centric Network (CCN) original routing concept [1, 50]. In this approach, content-producers periodically flood the entire network with announcing prefixes carried out by interest packets. Hereafter, we call this implementation $OSPF_{Like}$. A router does not monitor the connectivity to its neighbors and, therefore, routers forward the prefix announcement interest to update periodically the path to producer. Network-wide recurrent flooding increases the routing signaling overhead proportionally to the network size and to the number of content prefixes. Moreover, since $OSPF_{Like}$ and DCR consider the same distance vector routing techniques, we concentrate our comparison on $OSPF_{Like}$ and we do not evaluate specific details of DCR proposal.

As mentioned before, Named-Data Link State Routing (NLSR) is a producer-oriented approach that avoids flooding procedure. NLSR uses a hop-by-hop procedure for database synchronization. Each NLSR router maintains the full view of the network in a local database called Link State DataBase. We omit optimizations and details that do not compromise the performance comparison, and we call our implementation by $NLSR_{Like}$.

A cluster of machines runs the CRoS-NDN controller functions as a locally centralized entity. These machines share a database that stores both the named-data location and the routers adjacency information for a single controller. Table 1 presents the parameters used for deriving the expressions for each scheme. Table 2 presents the lower bounds for data delivery efficiency of each routing scheme. The expressions consider that all network links have the same **L**ink **D**elay, L_d, each **C**onsumer sends interests and receives data at a constant **R**ate, C_r. Moreover, we consider the worst case scenario, in which consumer to producer and also router to controller distance equals network diameter **H**ops, H. Hence, without caching, the lower bound for the optimal efficiency equals $1/H$.

In the next section, we derive expressions to discuss the limiting factors of the analyzed schemes, namely ARP_{Like}, $OSPF_{Like}$, $NLSR_{Like}$, and our own CRoS-NDN proposal.

4.1 Data delivery efficiency lower bounds

4.1.1 *Address resolution protocol (ARP) like*

Figure 2 presents the interest time sequence for ARP_{Like} procedures. In ARP_{Like} a PIT-entry timeout triggers the removal of the associated FIB entry, as in CRoS-NDN procedure. ARP_{Like} efficiency depends on the fraction of interests that hit an existing FIB entry, which is equal to the complementary probability of **F**IB-**M**iss fraction, $1 - F_m$. ARP_{Like} router straightly forwards to producer interests with FIB hit. Otherwise, the router floods the interest on its links. The higher is the fraction of directly forwarded interests, $1 - F_m$, the closer ARP_{Like} efficiency becomes equal to $1/H$, the worst case scenario without requiring flooding. The higher is the fraction of flooded interests, F_m, the lower is the ARP_{Like} efficiency. In large networks with restricted diameter ($L >> H$), if consumer traffic shows uncorrelated interest prefixes and router FIB has insufficient memory to support all content prefixes simultaneously, then, ARP_{Like} router recurrently floods interests and the efficiency tends to zero due to FIB entry replacement. Under router unbounded FIB-memory assumption and after enough time, ARP_{Like} routers store routes to all prefixes and FIB misses tend to zero, and in this case, ARP_{Like} efficiency tends to the optimal value. Therefore, we express the lower bound of Data Delivered Efficiency by $ARP_{Like} = \frac{1}{(F_m.L+(1-F_m)H)}$.

Table 1 Parameters of the routing/forwarding scheme expressions

Parameter - Description	Parameter - Description
N - Number of **N**odes	T_r - **T**opology change **R**ate
L - Number of **L**inks	L_d - **L**ink **D**elay
H - Network diameter **H**ops	DDE - **D**ata **D**elivery **E**fficiency
C_r - **C**onsumer **R**ate	RTD - Max **R**ound **T**rip **D**elay
AP - **A**nnounced **P**refixes	C_d - **C**onsumer-producer **D**elay
A_r - **A**nnouncement **R**ate	A_d - **A**nnouncement **D**elay
F_m - **F**IB **M**iss ratio	T_d - **T**opology-update **D**elay
K_r - **K**eepalive **R**ate	DDD - **D**ata **D**elivery **D**elay

Table 2 Data delivery efficiency lower bound expressions

Scheme	Data Delivery Efficiency (DDE)
ARP_{Like}	$\frac{1}{(F_m.L+(1-F_m)H)}$
$OSPF_{Like}$	$\frac{C_r(1-F_m)}{(AP.L.K_r+C_r.H)}$
$NLSR_{Like}$	$\frac{C_r}{(L(2.K_r+4.T_r+5.A_r)+C_r.H(F_m+1))}$
$CRoS-NDN$	$\frac{C_r}{(L(2.K_r+T_r)+H(N.T_r+A_r+C_r(F_m+1)))}$

4.1.2 *Open shortest path first (OSPF) like*

Figure 2 presents the interest time sequence of $OSPF_{Like}$ procedures. Like our CRoS-NDN scheme, $OSPF_{Like}$ routers have no knowledge of network topology, however, $OSPF_{Like}$ forwarding decisions follow the local view of the received prefix announcements. If a router receives the same announcement from multiple interfaces, then, it ranks output interfaces according to hop distance to producer. Moreover, unlike CRoS-NDN, $OSPF_{Like}$ router stores all available content prefixes simultaneously in its FIB memory. Thus, the number of interests in the network depends on the rate of consumer interests, C_r, the rate of periodic content announcements, corresponding to K_r and the number of announced prefixes, AP. Consumer interests traverse H links to reach producer, expressed by $C_r.H$ denominator factor. $OSPF_{Like}$ periodically floods all announced prefixes, AP, on all network links, L, with rate K_r, given by $AP.L.K_r$ denominator factor. The number of content data received by the Consumer is equal to the fraction of consumer interest rate that hit a FIB entry and, thus $C_r.(1-F_m)$ is the numerator of the efficiency expression. Then, a $OSPF_{Like}$ lower bound of Data Delivered Efficiency is expressed by $\frac{C_r(1-F_m)}{(AP.L.K_r+C_r.H)}$. We can note that $OSPF_{Like}$ efficiency decreases with the number of content prefixes, AP, the rate of periodic prefix announcements, K_r, the number of networks links, L, the rate of consumer interests, Cr, and network diameter Hops, H.

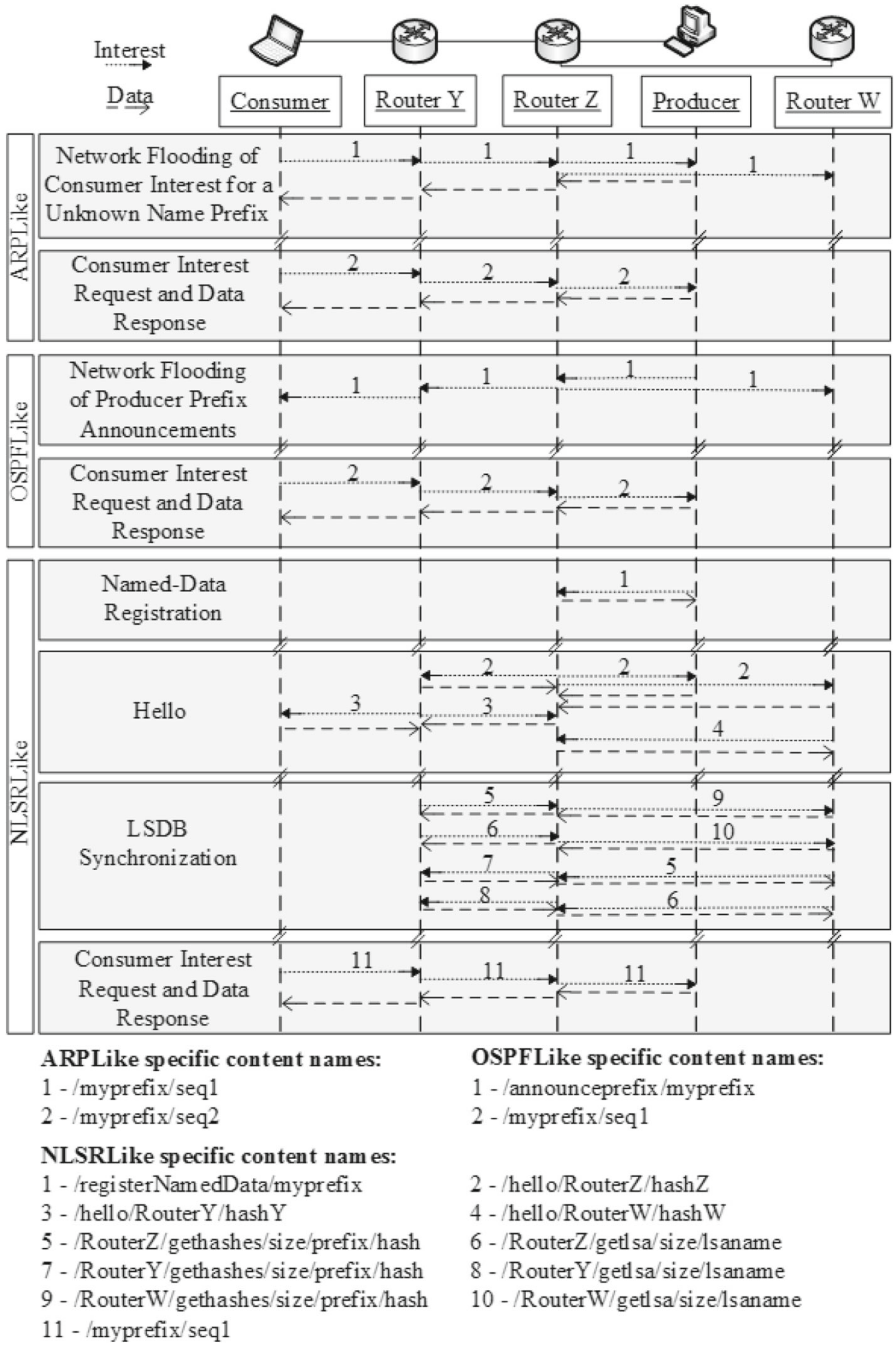


Fig. 2 Interest/Data sequences for studied routing/forwarding schemes

4.1.3 Named-data link state routing (NLSR) like

Figure 2 presents the interest sequence for $NLSR_{Like}$ procedures. $NLSR_{Like}$ employs a local database called Link State DataBase (LSDB) that stores the network topology and the content producer locations using database entries called Link State Advertisements (LSAs). Each router computes the hash for each LSA name [53], builds a tree with branches based on LSA-name prefixes, and sums the hashes of LSA names that share equal prefix to compute the hash for each branch. Then, it builds a hash tree for the prefixes of LSA names and the LSDB hash is the root hash of this tree. Producer registers the content prefix in its access router, using Named-Data Registration procedure. Then, the router updates its local

LSDB with a prefix-LSA. Neighbor routers exchange periodic interests to identify router adjacency, verify local connectivity, and compare their LSDB hashes (Hello procedure). Each router registers its neighbors in its local LSDB with an adjacency-LSA. If LSDB hashes of two neighbor routers differ, these routers initiate the LSDB Synchronization procedure that recursively exchange the branch hashes of LSA name prefix with hash differences until the branch leaf is reached. Then, the LSA difference is updated. Each router builds the network topology and the content prefix to producer identifier map based on its local LSDB and, then, the router determines locally the output interface upon consumer interest reception. $NLSR_{Like}$ routers monitor their neighbors sending keep alive interests on all links, using the Hello procedure, corresponding to $2.L.K_r$ messages in the efficiency denominator. The NLSR authors have defined prefix-LSA as `/< router_name>/LsType.2/LsId.<ID>/< version>` and adjacency-LSA as `/< router_name>/LsType.1/< version>`, four and three components, respectively. Each component results in an interest per link during LSDB synchronization to navigate from the root to the leaf of the LSDB hash tree, and one additional interest to update the new LSA, hence $L(5.A_r + 4.T_r)$ denominator factor. Producers announce new prefixes with rate A_r and topology changes with rate T_r. Furthermore, besides the consumer to producer interest hops given by $C_r.H$, $NLSR_{Like}$ FIB miss F_m takes one interest to control plane per router in the path from consumer to producer expressed by $C_r.H.F_m$. Hence, an $NLSR_{Like}$ lower bound of Data Delivered Efficiency is expressed by $\frac{C_r}{(L(2.K_r+4.T_r+5.A_r)+C_r.H(F_m+1))}$.

4.1.4 Our proposal CRoS-NDN

The numerator of CRoS-NDN expression for efficiency lower bound corresponds to consumer received content rate and equals consumer interest request rate, C_r. The denominator is composed of: i) $2.L.K_r$ factor that corresponds to the Hello interests for router-neighbor monitoring; ii) $T_r.L$ factor that corresponds to Controller Discovery procedure when controller-discovery interests are flooded after each topology change; iii) $H.N.T_r$ that corresponds to the Router-Registration procedure, when all nodes register in controller after each topology change; iv) $H.A_r$ that corresponds to the Named-Data Registration procedure, when producers register available content prefixes at the controller with A_r rate; v) $H.C_r.F_m$ that corresponds to the Route Request procedure when consumer sends to controller a route request upon consumer interest FIB miss; and vi) $H.C_r$ that corresponds to consumer to producer interests. A lower bound for Data Delivery Efficiency of our proposal CRoS-NDN is $\frac{C_r}{(L(2.K_r+T_r)+H(N.T_r+A_r+C_r(F_m+1)))}$.

4.2 Data delivery delay upper bounds

Data delivery delay (*DDD*) is another important performance indicator that corresponds to the delay between consumer content request and consumer content reception. *DDD*, see Table 3, sums three delay components: C_d - delay between consumer interest dispatch and content reception; A_d - delay between producer announcement of content prefix and network wide reach; and T_d - delay between a topology change and network forwarding rules convergence. In the worst case, the routing scheme converges upon any topology change adding T_d, afterwards producer can announce its content (A_d), and, finally, consumer can ask for and receive the content (C_d). Not all schemes, however, pass through these three phases and, consequently, some *DDD* components equal zero in some cases. The maximum **R**ound **T**rip **D**elay, RTD, between any pair of routers equals the diameter delay $RTD = 2.H.L_d$. In the scenario without caching, the optimal *DDD* equals *RTD*.

The C_d component considers the round trip delay between consumer and producer for all schemes, except CRoS-NDN. In the worst case, CRoS-NDN consumer first asks the controller a new route to content producer, in which case this additional procedure adds the round trip delay between consumer and controller.

The A_d component affects only the schemes where the producer proa-ctively announces content prefixes and, therefore, for ARP_{Like} A_d equals zero. $OSPF_{Like}$ and CRoS-NDN prefix announcement adds to A_d the one way producer to consumer delay and the one way producer to controller delay, respectively. $NLSR_{Like}$ prefix announcement requires database synchronization. For each hop in the path from producer to consumer, $NLSR_{Like}$ adds to A_d the LSDB hash exchange interval $\frac{1}{K_r}$ and the prefix-LSA exchange delay. Prefix-LSA exchange requires five request and response sequential iterations and, then, sums the delay $5.RTD$. Four iterations are required to exchange the branch hashes of the four components of LSA name and one additional iteration to exchange the LSA.

The T_d component only affects schemes in which routers monitor network topology changes. ARP_{Like} does not monitor topology changes and, consequently, T_d equals zero. Although $OSPF_{Like}$ routers do not monitor topology, prefix-announcement periodic interval delays

Table 3 Upper bound expressions for Data Delivery Delay (DDD) components

Scheme	C_d	A_d	T_d
ARP_{Like}	RTD	0	0
$OSPF_{Like}$	RTD	$\frac{RTD}{2}$	$\frac{1}{K_r}$
$NLSR_{Like}$	RTD	$5.RTD + \frac{H}{K_r}$	$4.RTD + \frac{H}{K_r}$
CRoS-NDN	$2.RTD$	$\frac{RTD}{2}$	$\frac{3.RTD}{2} + \frac{1}{K_r}$

new paths convergence and adds $\frac{1}{K_r}$ to T_d. $NLSR_{Like}$ routers update their local LSDB with a new adjacency-LSA upon local topology change. The LSDB synchronization for adjacency-LSA is one iteration faster than for prefix-LSA, because adjacency-LSA name has three components, one less than prefix-LSA. CRoS-NDN router periodically monitors connectivity to its neighbors at interval $\frac{1}{K_r}$ adding this value to T_d. Additionally, topology changes can incur changes in path from router to controller. In this case, CRoS-NDN router needs to discover a new path to the controller and re-register itself at the controller. Controller discovery adds the router to controller round trip delay and registration renewal adds another router to controller one-way delay to T_d.

All simulation results obtained for Data Delivery Efficiency (DDE) are greater than the lower bound and all Data Delivery Delay (DDD) results are lower than the upper bound, validating the derived expressions.

4.3 Discussion

We observe that the higher is the number of announced prefixes (AP), the better is CRoS-NDN and $NLSR_{Like}$ efficiency, while $OSPF_{Like}$ behavior is the contrary. CRoS-NDN and $NLSR_{Like}$ only announce new prefixes with rate A_r while $OSPF_{Like}$ periodically re-announces all prefixes (AP) with keep alive rate (K_r). On the other hand, this $OSPF_{Like}$ comparative disadvantage reduces with the growth of topology change rate (T_r) because $OSPF_{Like}$ routers do not monitor topology changes and, thus, it does not account for the topology change rate (T_r). CRoS-NDN shows a better efficiency than $NLSR_{Like}$ for scenarios with high number of prefix announcements. The CRoS-NDN efficiency decrease is proportional to the prefix announcement rate and to the network diameter in number of hops $H.A_r$, while $NLSR_{Like}$ efficiency decrease is proportional to prefix announcement rate and to the number of network links $L.A_r$. We can also observe that the higher is the rate of interests for prefixes not installed in FIB $C_r.F_m$, the better is CRoS-NDN efficiency compared to ARP_{Like}. ARP_{Like} floods interests without FIB hit and the efficiency decreases proportionally to the number of links $L.C_r.F_m$. Unlike ARP_{Like}, CRoS-NDN efficiency decreases proportionally to network diameter in number of hops $H.A_r + H.C_r.F_m$, $H.A_r$ interest hops for the producer to register the content at the controller and $H.C_r.F_m$ interest hops for the consumer to request new routes from the controller. In addition, $OSPF_{Like}$ efficiency also decreases as FIB miss, $C_r.F_m$, increases.

Concerning Data Delivery Delay DDD, the lower is the keep-alive rate, K_r, the greater is DDD for $OSPF_{Like}$, $NLSR_{Like}$, and CRoS-NDN strategies. Particularly, for $\frac{1}{K_r} >> L_d$, L_d factor becomes negligible. Then, ARP_{Like} delay tends to 0, $OSPF_{Like}$ delay tends to $\frac{1}{K_r}$, $NLSR_{Like}$ delay tends to $\frac{H}{K_r}$, and CRoS-NDN delay tends to $\frac{1}{K_r}$. Albeit smaller K_r value reduces signaling overhead, it increases DDD for $OSPF_{Like}$, CRoS-NDN, and $NLSR_{Like}$. We simulated different scenarios and the obtained results stay under the bound values, validating the mathematical expressions.

5 Numerical results

We implemented the NDN schemes in the ndnSIM [60] simulator that reproduces the NDN model with a customizable forwarding layer, which exposes customizable decisions on packet forwarding events. Accordingly, in our simulations, each scheme employs a specific forwarding strategy and specific applications to execute its procedures. Our results are for one controller randomly locate. Figure 3 shows the block diagram of our NDN node implementation on ndnSIM. We implemented[2] two node modules to manipulate FIB and PIT entries based on data names: one executes specific forwarding strategy for each scheme and the other consumes/produces specific data packets related to each routing scheme. The two modules use internal calls to manipulate FIB, PIT, CS, and other state information.

The simulation data presents mean results with 95% confidence interval, and individual consumers perceive different values depending on its position in the network. Mean and maximum errors are specified or graphically represented for the sake of clarity. In each simulation round, controller position, consumers, and producers are randomly chosen. In addition, like other works [6, 61], the simulations employ ISP-like topologies based on the largest connected component of Rocketfuel's topologies, a mapping technique that measures real router-level ISP topologies. Our simulations consider link bandwidth, link delay, queuing under congestion, packet drop under queue overflow, and zero switch delay values provided by the Rocketfuel's topologies. When contrary is not stated, we use the AS 1755 topology with 163 nodes and 366 links. It is worth noting that the network mean distance is 7.36 hops, the diameter is 22 hops, and the respective reference values for the data delivery efficiency are $DDE = 1/7.36 = 0.14$ for the mean case, and $DDE = 1/H = 0.05$ for the worst case. We choose the AS 1755 as the main topology because it presents a high number of links in comparison with diameter, $L >> H$, to stress the flooding negative effect on efficiency. Furthermore, the keep-alive rate value K_r is set to 0.1 for the $OSPF_{Like}$ periodic prefix announcement, like in OSPF, and for the $NLSR_{Like}$/CRoS-NDN Hello procedure, like in NLSR [53]. We use equal $K_r = 0.1$ values in order to ensure a fair comparison and we point that higher (lower) K_r values decrease (increase) the efficiency and increase (decrease) the data delivery

[2] We have to work a lot on the ndnSIM code to achieve a successful implementation of the schemes. A version of our simulator can be obtained at https://github.com/jvitor3/CRoS-NDN.

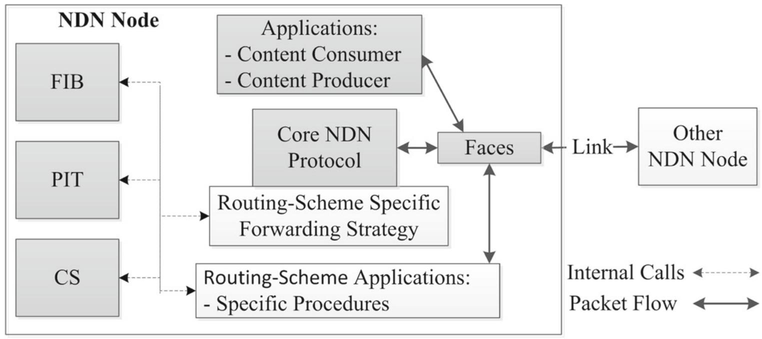


Fig. 3 Customized ndnSIM node for all routing/forwarding schemes

delay for these three schemes; however, different K_r values do not change the comparative behavior of the schemes with the increase in the number of prefixes. More importantly, we set values for simulation parameters in order to exhibit specific comparative results that would be otherwise obfuscated. We would like to emphasize the purpose of these parameter values is to make explicit individual limitation factors of each scheme and that all results consider the signaling overhead of each scheme.

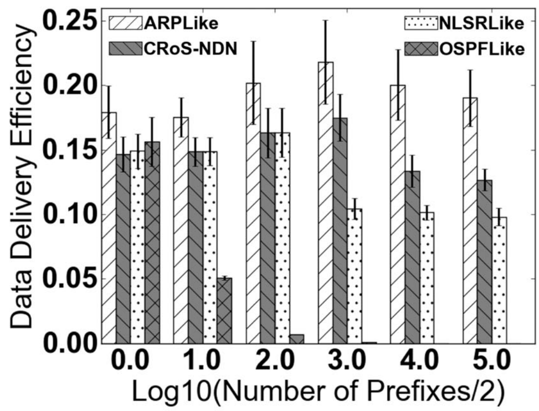
5.1 Number of prefixes increase for a restricted FIB size

In the first set of simulations, we evaluate the performance behavior of Data Delivery Efficiency when the number of prefixes[3] increases by five orders of magnitude, from 2 to 200,000, for a restricted FIB size. Figure 4a shows that $OSPF_{Like}$ does not scale well when the number of prefixes increases, even when considering router with unlimited FIB memory, because it has to periodically announce all available prefixes. $OSPF_{Like}$ data delivery efficiency sharply decreases from 0.15 to zero. It is worth noting that smaller K_r values reduce the factor by which $OSPF_{Like}$ efficiency decreases with the number of prefixes, but it does not change the trend. On the other hand, ARP_{Like}, $NLSR_{Like}$, and CRoS-NDN efficiency shows little variation when the number of prefixes increase, because these schemes avoid the periodic network flooding. We note that the producer announces 20 new prefixes per second and, therefore, for a higher number of prefixes, CRoS-NDN and $NLSR_{Like}$ efficiency decreases due to prefix announcements running at the end of the simulated time of 500 s. The simulation considers two consumers and each one requests sequential data for one distinct prefix with rate of 40 interests per second.

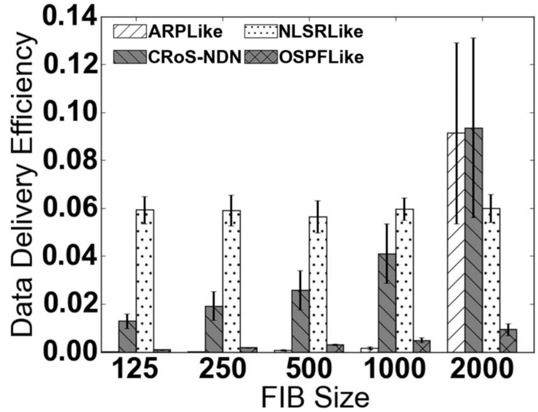
Figure 4b shows the Data Delivery Efficiency for constrained FIB memory. The results illustrate how ARP_{Like} does not scale well with the increase of the number of consumed prefixes beyond the FIB memory capacity. The simulation involves 2000 simultaneously consumed prefixes, each one with 1 interest per second, 2000 announced prefixes, and a growing number of FIB entries supported per router. We choose a number of announced prefixes that avoids $OSPF_{Like}$ sharp efficiency decrease, while showing the effect of FIB memory restriction. Under FIB memory restriction, all schemes replace the oldest installed entries with new ones according to a first-in first-out policy. ARP_{Like} efficiency suffers a lot from each FIB entry removal because it recurrently floods the network and, thus, the efficiency decreases proportionally to the number of network links. Unlike ARP_{Like}, no other scheme floods consumer interests upon FIB miss. $NLSR_{Like}$ efficiency shows very little variation in the number of supported FIB entries per router because $NLSR_{Like}$ router relies on its local control plane to reinstall the forwarding rules in the FIB. $OSPF_{Like}$ efficiency decreases due to the lack of memory for part of the prefixes, namely from 0.01 to 0.001 when the FIB memory reduces from 2000 to 125 entries. CRoS-NDN efficiency also reduces from 0.09 to 0.01, due to two combined factors: first, the additional hop distance from consumer to controller for route requests, and second, additional interests due to the early removal of FIB and PIT entries following FIB entry replacement. It is worth noticing that CRoS-NDN and OSPFlike exhibit the best efficiency improvement as function of FIB size, but CRoS-NDN outperforms OSPFlike by a factor of 10. This indicates that as routers memory size increases, CRoS-NDN efficiency will follow accordingly.

Figure 5 shows the processing time and the memory consumption of each simulation round for each scheme and for a growing number of prefixes. The results show the real consumed resources of our implementation and mirror the total consumption of CPU and memory for all network routers and the controller. The processing time value corresponds to the measured time required to simulate a round for a scheme. The memory corresponds to the consumed memory by a simulation round. $NLSR_{Like}$

[3] *Consumed prefixes* refer to prefixes of content requested by consumers and *announced prefixes*, or simply *prefixes*, refer to prefixes of content available at producers.



(a) $OSPF_{Like}$ DDE decrease with the number of prefixes.



(b) ARP_{Like} DDE decrease with FIB reduction.

Fig. 4 Data delivery efficiency as function of: **a** number of announced prefixes for unlimited FIB memory and **b** FIB sizes for 2000 simultaneously consumed prefixes

and $OSPF_{Like}$ show the highest resource consumption. $OSPF_{Like}$ simulation did not finish in a reasonable time for our hardware resources with more than 2000 prefixes. We note that controller and router-processing capacity is unlimited in our simulations, but memory capacity is restricted. CRoS-NDN shows less memory and time simulation requirements than $OSPF_{Like}$ and $NLSR_{Like}$, and similar requirements to ARP_{Like} for a growing number of prefixes.

In order to evaluate the robustness of our proposal compared to the other schemes, we consider a scenario of FIB restriction in which memory size is less than the number of 150 consumed prefixes. Figure 6 shows the Data Delivery Efficiency for a growing rate of consumer interests per prefix. The efficiency decreases due to congestion caused by the excessive number of requests, which is above link capacity. The results confirm $OSPF_{Like}$ low efficiency for a number of prefixes as low as 150. Additionally, Figure 6b shows an ARP_{Like} low efficiency due to a FIB memory smaller than required for the number of simultaneously requested prefixes.

5.2 Content-producer mobility

Mobility is a great challenge in today's Internet because of the IP-semantic overcharge that join identification and location. Unlike IP-based approaches, our proposal splits location and identification and, therefore, in this second set of simulations, we evaluate DDE and DDD robustness to content-producer mobility. In particular, we evaluate the robustness of CRoS-NDN efficiency and delay when increasing by one order of magnitude the number of consumed prefixes and the rate of interests per second. To highlight the trend in the comparison, the simulations consider 3 consumers per prefix, each consumer sending 20 interests per second, unlimited FIB memory, and a growing rate of producer mobility. Figures 7a and c present the data delivery efficiency for, respectively, 1 and 10 content prefixes in order to compare the combined effect of content mobility and the number of prefixes. To visualize the delay effect, Figs. 7b and d depict the data delivery delay of the respective scenarios. DDE and DDD metrics show the strongest variation in different ranges of Producer Moves Per Second. DDE decreases due to additional interests for signaling and to repeated requests for

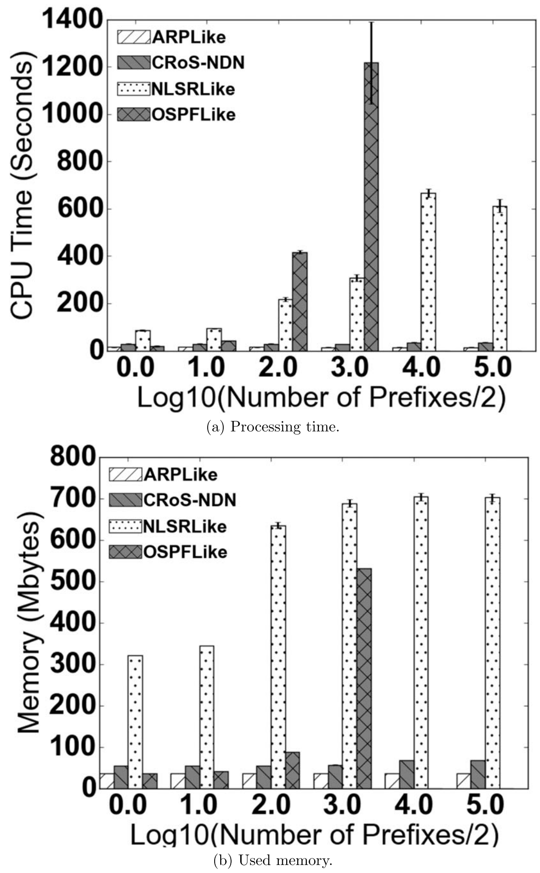


Fig. 5 Processing time and memory consumption for each simulation round. **a** Processing time. **b** Used memory

content that moved. ARP_{Like} increases the interest flooding, $NLSR_{Like}$ increases the signaling announcements, and $OSPF_{Like}$ increases the failed requests. DDD increases more sharply when mobility rate is too high above the K_r rate set to 0.1. K_r relates to the rate of Hello messages for CRoS-NDN/$NLSR_{Like}$ and to the rate of prefix announcements for $OSPF_{Like}$. Proactive schemes $OSPF_{Like}$/$NLSR_{Like}$ are more sensitive to mobility in DDD metric than reactive schemes CRoS-NDN/ARP_{Like}. Unlike the DDE decrease for ARP_{Like} , the growth of consumer-interest rate with the number of prefixes does not decrease $OSPF_{Like}$ and $NLSR_{Like}$ DDE. On the other hand, CRoS-NDN presents the best results with fast convergence and low overhead for producer location update, which corresponds to the best protocol for scenarios with content-producer mobility.

5.3 CRoS-NDN resiliency

We intuitively expect a fast convergence of our proposal at start up and after link failures. In the third set of experiments, we evaluate the resiliency characteristic of our proposal. The delay between the network events, start up or link failure, and the convergence to consumer request fulfillment give an indirect measure of the data delivery delay (*DDD*) metric that equals the sum of delays to announce prefixes, install routes, and receive data.

CRoS-NDN presents a faster convergence delay because it only depends on, first, the delay of routers to update their local information at the controller and, second, the delay of routers to receive new routes from the controller. Figure 8a shows the convergence delay at start up and at the recovery from a link failure to a secondary longer path. The slow convergence of $NLSR_{Like}$ is due to the hop-by-hop delay of database synchronization procedure, while the set up convergence takes even longer due to the great number of differences among the databases routers. ARP_{Like} and $OSPF_{Like}$ schemes, both of them, show similar and small delay values because ARP_{Like} immediately floods interests for unknown prefixes and $OSPF_{Like}$ convergence depends only on the producer-prefix announcement arrival to install new routes. The flooding procedure decreases the delay at the cost of increasing the overhead of messages that decrease the efficiency. Figure 8b shows

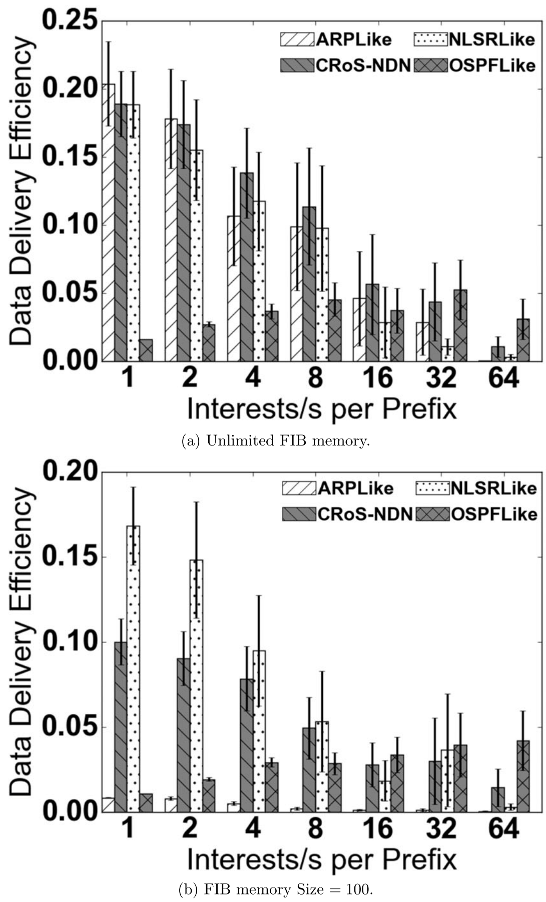


Fig. 6 Data delivery efficiency as a function of consumer-interests per prefix rate for: **a** unlimited FIB size and **b** FIB size = 100

direct measures for Data Delivery Delay, *DDD*, considering a variation of the Hello rate *Kr*. As expected from our analysis, $NSLR_{Like}$ delay decrease is higher when the Hello rate is increased.

CRoS-NDN shows a fast propagation of new routing information when compared with $NLSR_{Like}$, as illustrates Figure 8c. The producer announces one new prefix per second in the initial 100 s. The prefix announcement reduces $NLSR_{Like}$ efficiency due to the database synchronization packets and, additionally, $NLSR_{Like}$ shows a higher convergence delay. Figure 8d shows direct measures of Data Delivery Delay, *DDD*, considering different rates for the registration of new prefixes.

$NLSR_{Like}$ performance can be improved through direct flooding of new LSAs on the network, this way avoiding the slow convergence of the LSDB Synchronization procedure for new LSAs. Unlike $OSPF_{Like}$, $NLSR_{Like}$ avoids the need to recurrently flood content prefixes because $NLSR_{Like}$ routers synchronize their local LSDB databases, which avoids a similar $OSPF_{Like}$ efficiency decrease with the number of prefixes. On the other hand, the number of routers and the number of contents impose serious scalability limitations in terms of the amount of storage and processing power that each $NLSR_{Like}$ router must individually support, because each $NLSR_{Like}$ router must store locally the latest version of each LSA-adjacency and LSA-prefix in its LSDB.

5.4 Content delivery network (CDN) support

We evaluate CRoS-NDN efficiency when providing CDN functionalities over NDN. In particular, we evaluate the impact on global efficiency and delay of consumers registering cached copies of popular content. We restrict this evaluation to CRoS-NDN because $NLSR_{Like}$ and $OSPF_{Like}$ do not reach content copies outside the path to producer without additional prefix announcements which would cause an overhead too high, and ARP_{Like} does not announce content location. Figure 9 compares the data delivery efficiency and delay for the CRoS-NDN scheme with and without registration of content copies stored on consumers. Consumer nodes have unlimited cache capacity and routers have a limited cache capacity.

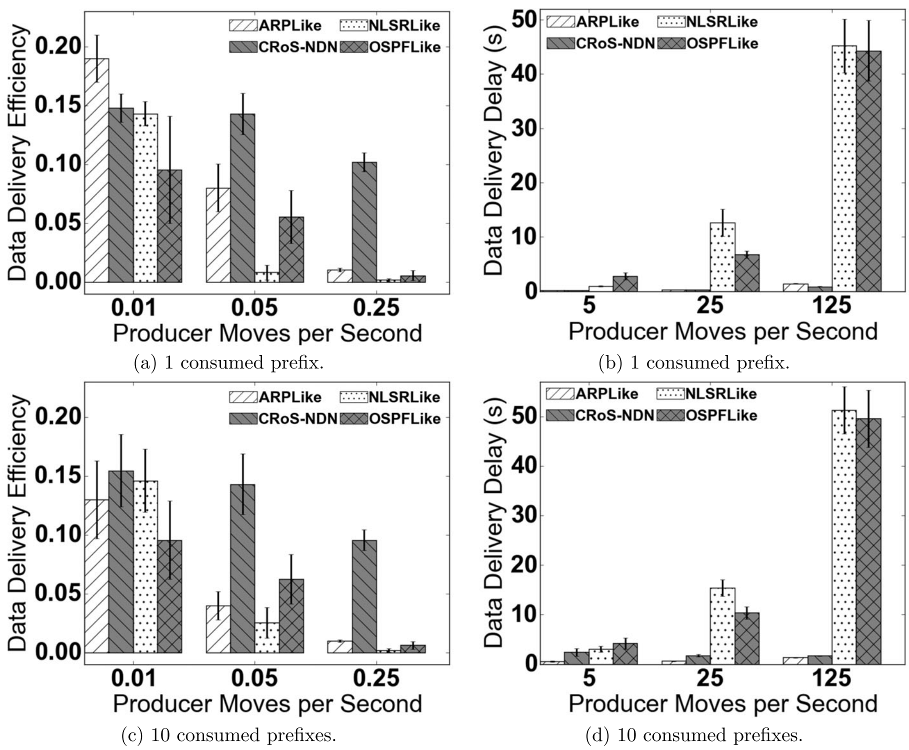


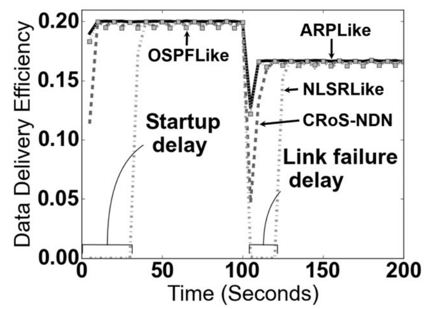
Fig. 7 Producer mobility impact on efficiency and delay. **a** 1 consumed prefix. **b** 1 consumed prefix. **c** 10 consumed prefixes. **d** 10 consumed prefixes

Each consumer requests the same content sequence for 20 s and stops. A new consumer starts at every 20 s. In the scenario with consumer registration of content copies, when the consumer stops, it informs the controller about content it cached by registering the names of these content items. Therefore, the controller has a new content copy location to consider when serving a route to the next route request. In this experiment, routers also cache content copies, but they do not register in the controller the content they have cached. Therefore, only routers that are in the path to registered copies have cache hits.

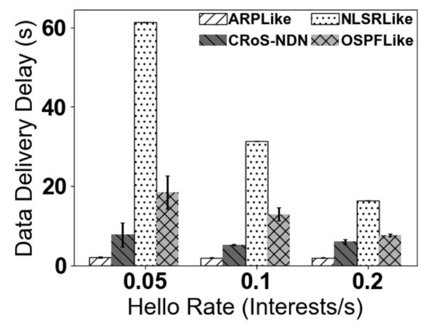
The efficiency gain and the delay reduction with the consumer registration of content copies depends on the cache capacity of the router and on the amount of requested data. When routers have higher caching capacity than the requested data, registering content copies has no advantage. Otherwise, when routers have smaller caching capacity than the requested data, registering content copies has a measurable efficiency gain and delay reduction. When routers have a small size capacity, the higher the consumer interest rate, the higher the number of requested content items and the higher the efficiency improvement. Figure 9a and b compare the mean delay perceived by all consumers for rates of 20 and 100 interests per second, respectively. Figure 9c and d show the efficiency for the 25^{th} consumer in the same simulation. Additionally, the efficiency increases with the consumer rate because the Hello rate is fixed at 0.1 interests per second.

Figure 10 shows the improvement of the CRoS-NDN efficiency with registration of content copies stored on consumers when compared with no-copy registration, when router cache size is insufficient for the requested data. Figure 10a shows that the highest efficiency gain occurs for the highest consumer rate (200) and a small cache size with 10 entries. Figure 10b shows no gain for consumer rate of 200 interests per second and a large cache size with 100,000 entries. Figures 10c and d show equivalent results in different topologies for cache sizes of 10 and 100,000 entries, respectively.

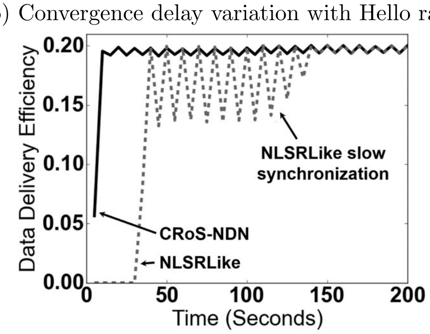
Announcing content copies location allows consumers to reach a closer copy that is outside the path to the producer. CRoS-NDN shows a low overhead for the registration of content copies location. This is in contrast to $OSPF_{Like}$ and $NLSR_{Like}$ that show poor performance when prefix-announcement rate increases. Content-prefix popularity presents a long tail distribution and, in this case, limited cache size in routers along the path to producer is



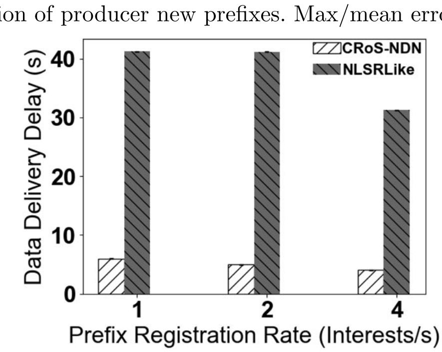
(a) Start up and recovery to secondary path. Max/mean error: 0.032/0.001.



(b) Convergence delay variation with Hello rate.



(c) Registration of producer new prefixes. Max/mean error: 0.006/0.001.



(d) Convergence delay variation with the rate of prefix registrations.

Fig. 8 a Efficiency behavior at start up and after a link failure. **b** *DDD* variation with the Hello rate *Kr*. **c** CRoS-NDN and $NLSR_{Like}$ convergence delay for a producer registering 100 new prefixes at 1 registration/s. **d** *DDD* variation with the registration rate

not effective. We believe that the registration of content copies location is a potential solution for CDN over NDN. A router can proxy interest for specific prefixes and cache the respective data closer to potential consumers for longer time windows.

5.5 Consumer requests with Zipf-Mandelbrot distribution

In this last set of simulations, we evaluate CRoS-NDN when consumers are requesting content with a Zipf-Mandelbrot distribution for the prefix popularity, as used by Carofiglio et al. [62] and experimentally verified by Cha

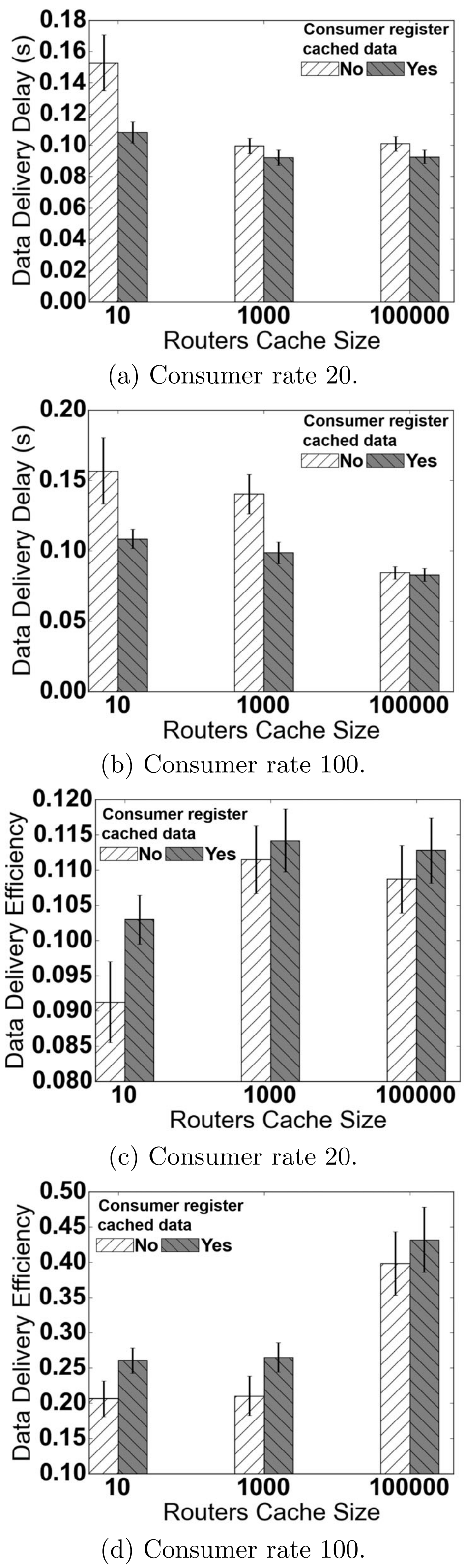


Fig. 9 Consumer registration of content copies impact on efficiency and delay. **a** Consumer rate 20. **b** Consumer rate 100. **c** Consumer rate 20. **d** Consumer rate 100

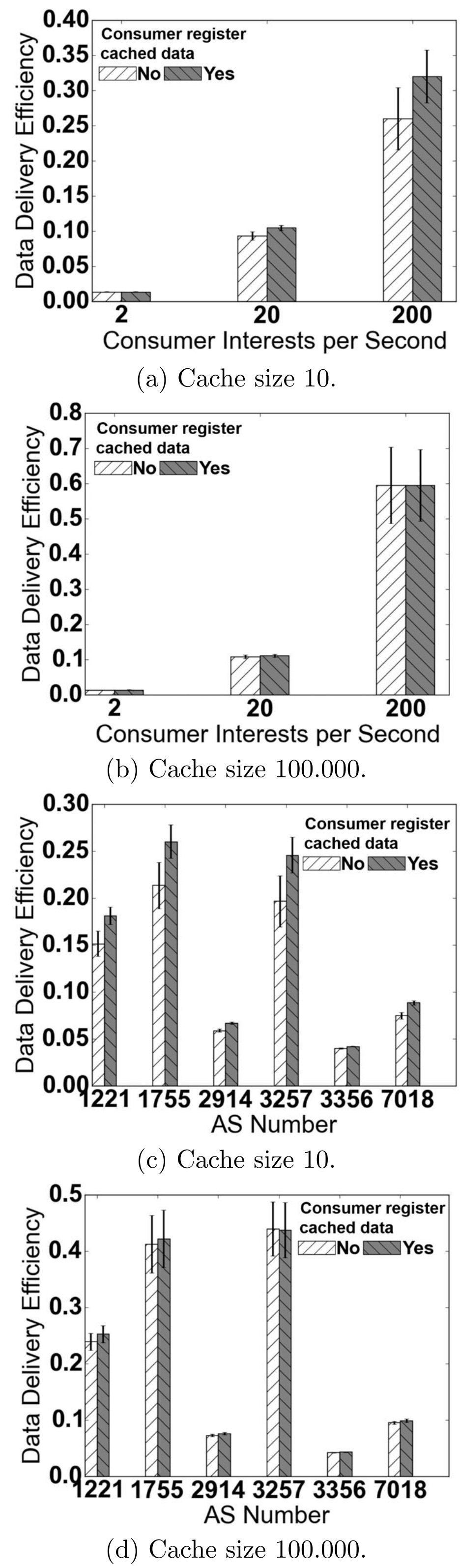


Fig. 10 Consumer registration of content copies in different cache sizes and topologies. **a** Cache size 10. **b** Cache size 100.000. **c** Cache size 10. **d** Cache size 100.000

et al. for the YouTube case [63]. We restrict this evaluation to CRoS-NDN because our computational resources cannot handle the $NLSR_{Like}$ and $OSPF_{Like}$ implementations for these scenarios. We consider constrained FIB memory, a growing rate of consumer interests, and short/long tail for the popularity distribution of content prefixes. We found that the efficiency decreases when the tail of the prefix popularity distribution increases and, at the same time, there is insufficient memory for most of the available prefixes. The efficiency decreases for three reasons. First, the higher rate of route requests to the controller halves the efficiency with one route request per consumer interest in the worst case. Second, an intrinsic characteristic of ndnSIM simulator erases PIT entries on removal of corresponding FIB entry resulting in additional repeated interests from consumer for unanswered requests. Third, link congestion at higher consumer rates affects the controller-access link and causes additional interest retransmission in the worst case.

The longer is the tail of the prefix popularity distribution, i.e. lower α parameter of the Zipf distribution, the higher are both the rate of FIB misses and the rate of route requests to controller when the FIB memory is insufficient for all content prefixes. Therefore, the efficiency decreases. We choose the number of prefixes (3000), the FIB size (100, 1000, and 3000 entries), and the α values (0.7 and 1.4) in order to highlight this behavior. Figure 11a shows the efficiency with a single consumer and a growing rate of consumer interests per second. Figure 11b shows the efficiency with a growing number of consumers, each consumer with a fixed rate of 50 interests per second. Figure 11c and d show the rate of route requests received by the controller for single consumer and multiple consumers scenarios, respectively. The higher rate of consumer interests causes higher rates of route requests. Furthermore, a higher number of consumers with the same prefix popularity distribution causes an aggregated prefix popularity distribution with longer tail, and, therefore, decreases the efficiency due to a high rate of route requests. The aggregated rate of consumer interests is equal in Fig. 11a, b, c and d. In addition, for small FIB size (100) and high rate of route requests, the FIB entry time in memory is lower than the round trip time and, thus, the early removal of a FIB entry and the associated PIT entries reduce the efficiency because of repeated route requests for the same prefix. For the sake of clarity, we omitted FIB size=3000 with $\alpha = 1.4$ and FIB size=1000 with $\alpha = 1.4$ curves to focus on worst cases.

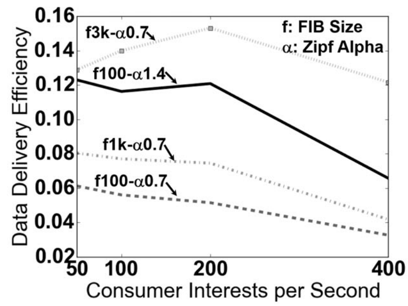
Figure 12 shows CRoS-NDN scalability and efficiency for 3 orders of magnitude ratios of number of prefixes to FIB size. The results consider 4 orders of magnitude increase in the FIB size. In this scenario, a single consumer requests content with 100 interests per second. The higher is the number of prefixes to FIB size ratio and higher is the Zipf α parameter, the lower is the efficiency. It is worth mentioning that the higher is the number of prefixes, the lower is the ratio of requested prefixes to all prefixes considering a fixed time window and a fixed rate of consumer interests. As such, the efficiency decreases (stabilizes) for $\alpha = 0.7$ ($\alpha = 1.4$) with higher number of prefixes due to the limited simulation time.

Figures 11 and 12 also point to CRoS-NDN potential bottleneck at the controller access link. The rate of route requests increases when there is insufficient FIB memory for most of the solicited prefixes due to the long tail of prefix popularity distribution at core routers. In this scenario, the controller access link congests and causes interests retransmissions. The additional interests further reduce the efficiency.

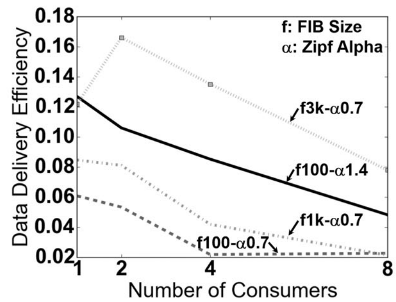
6 The CRoS-NDN tunnel extension

As discussed above, an insufficient FIB memory for most of the solicited prefixes and the long tail of prefix popularity distribution at core routers increase the amount of FIB misses leading to a higher route request rate, and therefore decreases the performance. The increase of route requests causes congestion of the controller access link and, consequently, the number of required interest retransmissions increases. To mitigate this, we propose the CRoS-NDN Tunnel Extension, a tunneling approach [32], which reduces the FIB memory requirement at core routers because the number of prefixes employed to identify the destination network segments [64] is much less than the number of content prefixes. The modified Route Installation procedure installs a route to network segments, and consumer access-router adds the identifier of the producer network segment as a prefix in interest names. Routers in the destination segment remove this prefix and forward the interest to producer. Access-routers manipulate the data packets names according to the backward direction to consumer. We present in this section the simulation results for the simplified case in which a segment identifies a single router that provides the worst prefix aggregation result.

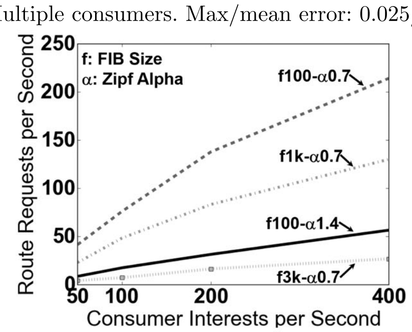
In order to evaluate CRoS-NDN Tunnel Extension performance in the scenario with insufficient FIB memory for the requested prefixes, we repeated the experiments with consumer interests following the Zipf-Mandelbrot distribution for content prefix popularity and a growing number of consumers. Figure 13a shows the comparative results for the original CRoS-NDN scheme and the CRoS-NDN Tunnel Extension. The results show that the CRoS-NDN Tunnel Extension reduces both the route request growth as a function of the number of consumers and the corresponding decrease of the data delivery



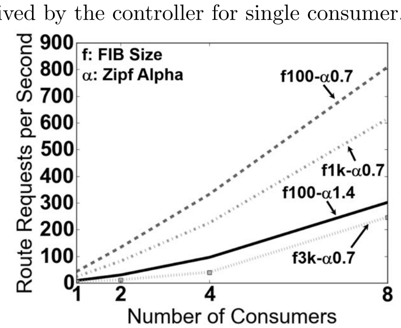
(a) Single consumer. Max/mean error: 0.029/0.021.



(b) Multiple consumers. Max/mean error: 0.025/0.018.



(c) Route requests received by the controller for single consumer. Max/mean error: 25/8.



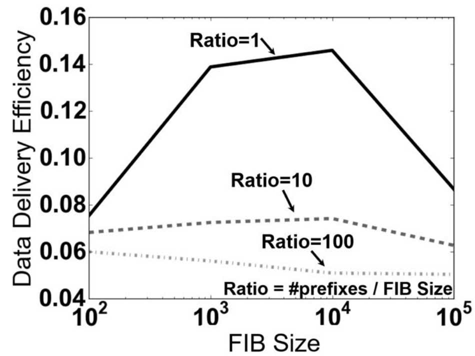
(d) Route requests received by the controller for multiple consumers. Max/mean error: 69/16.

Fig. 11 CRoS-NDN data-delivery efficiency as function of consumer interests. **b** and **d** consider multiple consumers and a fixed rate of 50 interest/s per consumer. **a** Single consumer. Max/mean error: 0.029/0.021. **b** Multiple consumers. Max/mean error: 0.025/0.018. **c** Route requests received by the controller for single consumer. Max/mean error: 25/8. **d** Route requests received by the controller for multiple consumers. Max/mean error: 69/16

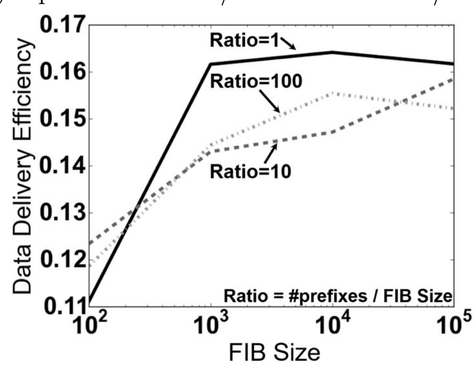
efficiency. The data-delivery efficiency for CRoS-NDN Tunnel Extension, which curves are indicated by the suffix TE, is higher than 0.08 compared to 0.02 for CRoS-NDN. Figure 13b shows a rate of route requests for CRoS-NDN Tunnel Extension lower than 70 compared to 900 for CRoS-NDN.

7 Conclusion

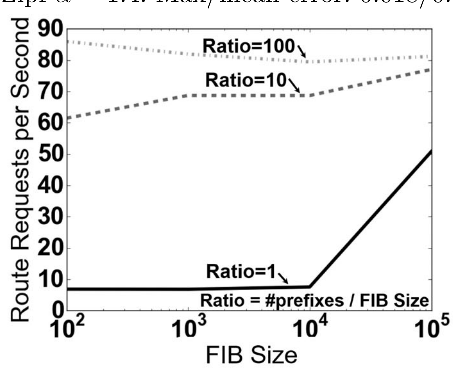
We presented and analyzed the performance of CRoS-NDN, a named data routing scheme that preserves the original NDN features. While relying on a logically centralized controller for routing decisions, CRoS-NDN involves two phases: Bootstrap phase, and Named-Data



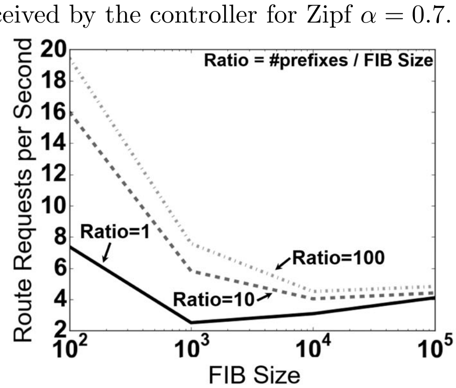
(a) Zipf $\alpha = 0.7$. Max/mean error: 0.011/0.009.



(b) Zipf $\alpha = 1.4$. Max/mean error: 0.018/0.016.

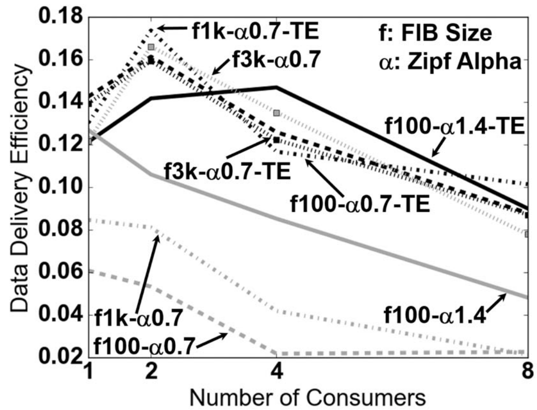


(c) Route requests received by the controller for Zipf $\alpha = 0.7$. Max/mean error: 7/4.

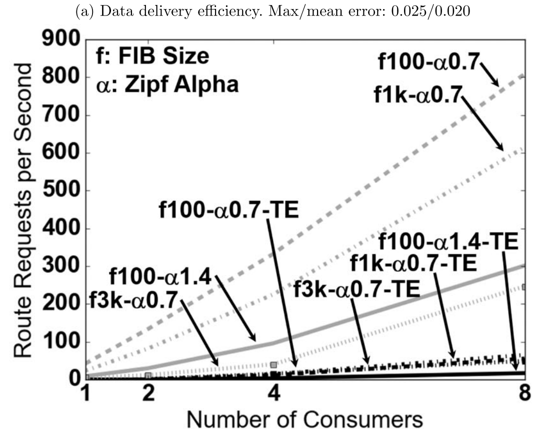


(d) Route requests received by the controller for Zipf $\alpha = 1.4$. Max/mean error: 2.6/0.5

Fig. 12 CRoS-NDN data-delivery efficiency for the ratio of number of prefixes to FIB size. Consumer interests follow the Zipf-Mandelbrot distribution for content-prefix popularity. **a** Zipf $\alpha = 0.7$. Max/mean error: 0.011/0.009. **b** Zipf $\alpha = 1.4$. Max/mean error: 0.018/0.016. **c** Route requests received by the controller for Zipf $\alpha = 0.7$. Max/mean error: 7/4. **d** Route requests received by the controller for Zipf $\alpha = 1.4$. Max/mean error: 2.6/0.5



(a) Data delivery efficiency. Max/mean error: 0.025/0.020



(b) Received route-request rate. Max/mean error: 69/16

Fig. 13 a Data delivery efficiency and **b** Route request rate for CRoS-NDN and CRoS-NDN Tunnel Extension (TE) as function of number of consumers. The simulation employs a rate of 50 interests/s per consumer.

Routing phase. The controller stores the content names, calculates routes from the consumer to the producer, and leverages global view of the network in order to avoid unnecessary control messaging overhead. Moreover, our scheme does not rely on prefix aggregation, enabling content placement/caching at in any location. This flexibility allows content copies placement closer to consumers, decreasing delivery latency and improving content mobility efficiency, analogous to CDN behavior. We derived lower-bound expressions for the efficiency and upper-bound expressions for the content delivery delay of our proposal and other known routing/forwarding schemes for NDN. Furthermore, we evaluated and compared these schemes using simulations.

The analysis and the simulation results show that CRoS-NDN presents superior performance compared to other schemes in terms of data delivery efficiency, robustness to FIB memory limitation, efficiency in handling producer mobility, and resiliency to link failure. Moreover, the results show that CRoS-NDN requires low processing time and low memory, and the data-delivery efficiency increases when consumer registers in the controller that data is cached. In order to mitigate a potential bottleneck at the access link to the controller, we proposed and evaluated the CRoS-NDN Tunnel Extension. The results show that the latter reduces the route requests to controller under FIB memory restriction.

For future work, we plan to evaluate the Afanasyev et al. proposal [28] combined with our CRoS-NDN scheme to avoid changes of content names introduced by the tunnel extension. In order to develop and evaluate our proposal in a real network environment with multiple controllers, we also plan to deploy our scheme in the Future Internet Testbed with Security (FITS) [65], employing the software distribution developed by Project CCNx (Content Centric Networking) and the Named-Data Networking Forwarding Daemon (NFD) distribution.

Abbreviations

ARP: Address Resolution Protocol; BGP: Border Gateway Protocol; CCFS: Controller-Based Caching and Forwarding Strategy; CDN: Content Distribution

Networks; CRoS-NDN: Controller-based Routing Scheme for Named-Data Networking; CS: Content Store; DCR: Distance-based Content Routing DDD: Data Delivery Delay; DDE: Data Delivery Efficiency; DDoS: Distributed Denial-of-Service; DHT: Distributed Hash Table; DNS: Domain Name System; EID: Endpoint Identifier; ETR: Egress Tunnel Router; FIB: Forwarding Information Base; ICN: Information Centric Network; IP: Internet Protocol; ISP: Internet Service Provider; LISPv Locator/ID Separation Protocol; LSA: Link State Advertisements; LSDB: Link State DataBase; NDN: Named-Data Networking; NLSR: Named-Data Link State Routing; ODR: On-Demand Routing; OSPF: Open Shortest Path First; OSPFN: OSPF Based Routing Protocol for Named Data Networking; PIT: Pending Interest Table; RLOC: Routing Locator; SAHAv Scalable Area-based Hierarchical architecture; SDLv Specification Description Language; SDN: Software Defined Networking; VoCCN: Voice-over Content-Centric Network

Acknowledgments
We acknowledge colleagues of the Grupo de Teleinformática e Automação (GTA/UFRJ) for their incentives and suggestions.

Authors' contributions
All authors read and approved the final manuscript.

Funding
This research is partially funded by CNPq, CAPES, FAPERJ, and FAPESP (2015/24514-9, 2015/24485-9, and 2014/50937-1).

Availability of data and materials
Please contact author for data requests.

Competing interests
The authors declare that they have no competing interests.

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Received: 29 April 2019 Accepted: 26 September 2019
Published online: 09 November 2019

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