# CRoS-NDN: Controller-based Routing Strategy for Named Data Networking

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***Abstract*—Named Data Networking focuses on the communicated data name, fundamentally changing the network task of locating and forwarding information. Additionally, the huge amount of content names challenges the scalability of techniques used for this task. This article proposes a strategy that consolidates the control plane on a dedicated node apart of switches responsible for the data plane. The proposal shows higher performance compared with others strategies identified in the literature. The comparison uses analytical modeling and simulation to measure convergence delay and efficiency in terms of useful and signaling traffic ratio. The results demonstrate the proposal superior performance with up to 75 % better signaling efficiency and more than 1000 seconds faster convergence time in an ISP simulated topology.**

## I. Introduction

Content-Centric Networking (CCN) [1] drastically changes network data location and forwarding task. CCN focus on content name and no longer on host network address to forward packets, as it is in the Internet today. This has the great advantage of not relying on a single host identifier to serve content requests. CCN store content copies in multiple places and, as a consequence, nearer the user rather than sending repeated requests to original source. Additionally, a CCN node aggregates parallel requests to the same content and forwards only one request ahead, again reducing the load on the content source. However, as the content amount is much greater than the host amount, the content location becomes one major challenge for CCN. To handle content location task in a scalable manner, CCN bonds content name to network location. Content located on the same network segment share the same name prefix. Additionally, CCN organizes content prefix names hierarchically according to network topology structure. This content location bond leads to summarized routing tables based on prefix pointers. Under these assumptions, CCN uses prefixes announcement routing schemes to disseminate content location on the network.

Nevertheless, this premise leads to the well known IP limitations related to mobility and multihoming. Content stored outside its original network segment are unreachable, except either content uses multiples names or each network segment advertises multiples prefixes. First option breaks the fundamental bond between name and content and it is unacceptable as it reduces aggregation and cache effects. Second option breaks the original CCN premise, *i.e.*, the bond between name and location, and it increases signaling overhead [2].

This work proposes the Controller-based Routing Strategy for Named Data Networking (CRoS-NDN). *CRoS-NDN* borrows Software-Defined Network (SDN) concepts, consolidating network information on controller nodes and simplifying forwarding nodes. *CRoS-NDN* natively runs on top of interest and content packets, thus it preserves CCN aggregation and caching properties and it paves the way out of IP dependent SDN solutions. Additionally, *CRoS-NDN* enhances prior work [3] restricting signaling network flooding.

This article compares *CRoS-NDN* performance to other routing strategies identified in the literature. The comparison defines two performance metrics: (i) content delivery delay and (ii) signaling efficiency. The presented analysis uses mathematical modeling, trend analysis and simulation to compare strategy performance. The analysis focus on scenarios with only one controller. Analyzed scenarios shows *CRoS-NDN* up to 75 % better signaling efficiency and more than 1000 seconds faster convergence time compared to the second highest *SE* for constrained memory strategy.

The rest of this paper is structured as follows. Section II presents *CRoS-NDN* proposal and compared strategies. Section III presents strategies performance comparison. Section IV describes the main related work. Finally, Section V concludes and presents future work.

## II. Proposed Strategy: CRoS-NDN

Controller-based Routing Strategy for Named Data Networking (CRoS-NDN) separates control and data planes and it consolidates control plane on a dedicated node, the controller. Control plane consolidation ensures network nodes a vantage point to register and request network information without flooding the entire network. *CRoS-NDN* nodes proactively register network information on controller and they reactively request new routes to controller upon consumer interests to locally unknown name prefixes.

*CRoS-NDN* reduces routing signaling overhead by restricting network interest flooding. Network nodes flood the network only to initially find the controller. Afterwards, controller search flooding occurs just upon node to controller interest timeout. Each *CRoS-NDN* node monitors its one hop neighbors and register any topology change in the controller. *CRoS-NDN* nodes also register local produced content name prefixes. Controller collects each network information peace and it acquires knowledge of the network topology and of content name prefix to producer node identifier map.

*CRoS-NDN* end-to-end route installation takes only one controller route request. Route requesting node informs its

identifier and the desired content name in interest route request to controller. Upon route request, first controller identifies the requesting node and locate the content producer node. Afterwards, controller computes node identifiers sequence path from consumer to producer and it answers the route request. Upon route request controller answer, requesting node builds a special interest that installs new FIB entries on each node through the network in the path to content producer. Although path calculation rely on node identifiers, content request interest forwarding rely only on content names.

Topology changes or content mobility can invalidate FIB entries installed on nodes. *CRoS-NDN* uses data plane feedback to remove invalid FIB entries on each node. Data plane interests without answer causes PIT entry expiration after interest lifetime timeout. *CRoS-NDN* links PIT entries timeout and the associated FIB entries removal.

In addition to lower signaling overhead, *CRoS-NDN* reduces FIB memory node requirements to the scale of simultaneous consumed prefixes. *CRoS-NDN* reuses FIB memory replacing old entries to new ones. This is in contrast to supporting all content prefixes available on the network irrespectively of user request profile. Algorithm 1 presents *CRoS-NDN* high level pseudo code.

**Algorithm 1** CRoS-NDN

**Require:** node *i*; *controller*;
**loop**
  *i* monitors neighbors and finds *controller*;
  **if** *i* neighbor list changes **then**
    *i* informs its new neighbor list to *controller*;
  **end if**
  **if** *i* has new local content producer prefix **then**
    *i* register local producer prefixes in *controller*;
  **end if**
  **if** *i* receives interest without FIB match **then**
    *i* requests a new route to *controller*;
    upon *controller* answer, *i* sends a special interest installing FIB entries on nodes path to producer;
  **end if**
  **if** *i* receives FIB entry installing interest to prefix *prefixA* **then**
    *i* adds FIB entry *prefixA* pointing to next hop and forwards the interest;
  **end if**
**end loop**

### A. Compared Strategies

*1) OSPFLike:* Open Shortest Path First Like (OSPFLike) strategy follows CCN original routing concept [1]. In contrast to *CRoS-NDN*, *OSPFLike* content producer nodes periodically flood the entire network with name prefix announcing interests. Each node forwards the prefix announcement interest without reliable delivery and, as a consequence, producer nodes must periodically refresh their announcement. Network wide recurrent flooding increases the routing signaling overhead in proportion to network size and to the number of different content prefixes.

Producer node adds a special prefix to announcing interest name. This prefix dispatch two actions on interest receiving nodes: i) node replicates the interest to all its interfaces; ii) node adds a new FIB entry with the announced prefix pointing to announcement incoming interface. *OSPFLike* invalid FIB entries removal copies the *CRoS-NDN* procedure, i.e., PIT entry timeout dispatch associated FIB entry removal.

*OSPFLike* nodes have no knowledge of network topology and their forwarding decisions follow the local view of the received prefix announcements. If a node receives the same announcement from multiple interfaces, them it ranks output interfaces according to hop distance to producer. Differently from *CRoS-NDN*, *OSPFLike* nodes stores all available content prefixes simultaneously on the their FIB memory.

*2) NLSRLike:* Named-data Link State Routing Like (NLSRLike) strategy, based on Hoque et al. work [4], replaces the *OSPFLike* periodic prefix announcement flooding by a database synchronizing scheme. This database, called Link State DataBase (LSDB), stores network topology and content producers information.

LSDB synchronizing scheme propagates only new information on the network. Neighbor nodes exchange LSDB hashes to verify local connectivity and to update consistency across the network on hop by hop basis. Whilst this strategy avoids flooding redundant information, each *NLSRLike* node must keep a local LSDB copy and the hash exchange interval delays the overall synchronization.

*NLSRLike* uses two LSDB entry types called Link State Advertisements (LSAs). First type, neighbor LSAs store node one hop directly connected neighbors information. Second type, prefix LSAs store content prefix to associated producer node identifier. If neighbor nodes LSDB hash does not match, these nodes exchange their LSAs hashes and they ask each other the new LSAs by their hash. Each node builds the network topology map and the content prefix to producer node map. Upon consumer interest reception each node evaluates locally the output interface using the Dijkstra algorithm.

*3) ARPLike:* Address Resolution Protocol Like (ARPLike) strategy, inspired in works [5] and [6], trades the *OSPFLike* proactive content prefix announcement to reactive content search using consumer interest flooding. Node floods the network whenever the incoming interest does not match any FIB entry. Upon content response arrival, *ARPLike* node updates its FIB adding a new entry with the content name prefix pointing to the content incoming interface. Node directly forwards subsequent interests with the same prefix using the new FIB entry. *ARPLike* uses the same *CRoS-NDN* procedure to remove invalid FIB entries, i.e., PIT entry timeout dispatch associated FIB entry removal.

If consumer interests have totally uncorrelated prefixes, nodes recurrently flood the network searching the content. This presents the worst case scenario, but recurrent flooding also occurs if the total number of prefixes is much higher than the entry number supported by node FIB memory and consumers have low prefix request correlation.

*4) Flooding: Flooding* node always replicates incoming interests to all interfaces. *Flooding* equals *ARPLike* behavior in FIB match fail scenario.

*5) Omniscient: Omniscient* is a reference strategy used to performance comparison. FIB entries are precomputed *a priori* leading to zero convergence delay and zero signaling overhead.

## III. Performance Comparison

Compared strategies use different approaches to convey content location and forwarding. *OSPFLike* and *NLSRLike* proactively announce content routing information on the network. *ARPLike* and *Flooding* reactively flood the network searching content. *CRoS-NDN* avoids network recurrent flooding by consolidating network information on a dedicated node, the controller. This section sounds each strategy performance.

Strategy performance comparison uses two metrics: content delivery delay and the signaling efficiency. First metric measures the delay between consumer content request and consumer content arrival. Depending on the used strategy, content delivery delay can be affected by: network convergence time after topology changes, prefix announcement propagation delay thorough network, and consumer to producer communication delay. Second metric, signaling efficiency measures the useful traffic fraction of total traffic. Useful traffic counts consumer received data packets and total traffic counts all interests sent in each network link.

This section compares strategies performance using mathematical modeling, see section III-A; trend analysis, see section III-B; and simulation, see section III-C.

### A. Mathematical model

This section models the content delivery delay (*CDD*) and the signaling efficiency (*SE*) metrics for each strategy using equations. The model considers the following premises:

- All network links have the same delay *LD*;
- Consumer sends interests and receives data at constant rate $CR$;
- Consumer to producer distance equals network diameter, worst case;
- Node to controller distance equals network diameter, worst case.

Table I list input and output parameters used in the model.

*CDD*, see equation 1, sums three delay components: *CD* - delay between consumer interest dispatch and content reception; *AD* - delay between producer content prefix announcement and network wide reach; and *TD* - delay between a topology change and network forwarding rules convergence. In worst case, first network converges upon any topology change adding *TD*, afterwards producer can announce its content *AD*, and finally consumer can ask the content *CD*. However, not all strategies pass through all these phases and *CDD* components equals zero in some cases.

First *CDD* component, *CD*, see equation 2, considers the round trip delay between consumer and producer for all strategies, except *CRoS-NDN*. In worst case, *CRoS-NDN* consumer node first asks the controller a new route to content producer and this procedure adds the round trip delay between consumer and controller.

Table I. Strategy comparison parameters

| Type | Variable | Description |
|---|---|---|
| Input | N | Number of network nodes |
| Input | L | Number of network links |
| Input | D | Network diameter |
| Input | CR | Consumer interest rate |
| Input | PS | Content prefix list size |
| Input | AR | Prefix announcement rate |
| Input | FF | FIB match fail fraction |
| Input | CCR | Connectivity check rate |
| Input | TR | Topology change rate |
| Input | LD | Link delay |
| Output | UF | Useful packets fraction |
| Output | SE | Signaling efficiency |
| Output | CD | Consumer to producer delay |
| Output | AD | Announcement delay |
| Output | TD | Topology convergence delay |
| Output | CDD | Content delivery delay |

Second *CDD* component, *AD*, see equation 3, affects only strategies in which producer proactively announces content prefixes. *Omniscient*, *Flooding* and *ARPLike* do not announce prefix and *AD* equals zero. *OSPFLike* and *CRoS-NDN* prefix announcement adds to *AD* the one way producer to consumer delay. *NLSRLike* prefix announcement uses the database synchronizing scheme. For each hop in between producer to consumer path, this scheme adds to *AD* the LSDB hash exchange interval $1/CCR$ and the neighbors LSA exchange delay. Neighbors LSA exchange delay sums two request and response sequential interactions, $4 \times LD$. In first interaction, node asks LSA hashes to neighbor, and in second interaction, node asks LSAs for new hashes to neighbor.

Last *CDD* component, *TD*, see equation 4, affects only strategies in which nodes keep track of network topology changes. *Omniscient*, *Flooding* and *ARPLike* do not monitor topology changes and *TD* equals zero. Although *OSPFLike* nodes do not monitor topology, prefix announcement periodic interval delays new paths convergence and it adds $1/CCR$ to *TD*. *NLSRLike* nodes updates their local LSDB with a new LSA upon local topology change. LSDB synchronism propagates the information to neighbors adding to *TD* the associated delay. This delay equals the one described above for *NLSRLike AD* component. *CRoS-NDN* node periodically monitors connectivity to its neighbors at interval $1/CCR$ adding this value to *TD*. Additionally, topology changes can incur node to controller path changes. In this case, *CRoS-NDN* node need to search a new path to controller and to renew its register in controller. Controller search adds to *TD* the node to controller round trip delay and register renewal adds another node to controller one way delay.

In order to access the signaling efficiency for each strategy, this work proposes to compute *UF*, the ratio of useful received content packets in relation to the total amount of interest packets transmitted on the network. *UF* denominator computes the number of interest packets multiplied by the number of interest traversed links, see equations 5.

$$CDD = CD + AD + TD \tag{1}$$

$$CD_1 = 2 \times LD \times D \quad {}_{1_{Omniscient,Flooding,ARPLike,OSPFLike,NLSRLike}} \tag{2a}$$

$$CD_{CRoS-NDN} = 4 \times LD \times D \tag{2b}$$

$$AD_2 = 0 \quad {}_{2_{Omniscient,Flooding,ARPLike}} \tag{3a}$$

$$AD_3 = LD \times D \quad {}_{3_{OSPFLike,CRoS-NDN}} \tag{3b}$$

$$AD_{NLSRLike} = D \times (4 \times LD + \frac{1}{CCR}) \tag{3c}$$

$$TD_4 = 0 \quad {}_{4_{Omniscient,Flooding,ARPLike}} \tag{4a}$$

$$TD_{OSPFLike} = \frac{1}{CCR} \tag{4b}$$

$$TD_{NLSRLike} = D \times (4 \times LD + \frac{1}{CCR}) \tag{4c}$$

$$TD_{CRoS-NDN} = 3 \times LD \times D + \frac{1}{CCR} \tag{4d}$$

$$UF_{Omniscient} = \frac{1}{D} \tag{5a}$$

$$UF_{Flooding} = \frac{1}{L} \tag{5b}$$

$$UF_{ARPLike} = \frac{1}{FF \times L + (1 - FF) \times D} \tag{5c}$$

$$UF_{OSPFLike} = \frac{CR}{PS \times L \times CCR + CR \times D} \tag{5d}$$

$$UF_{NLSRLike} = \frac{CR}{2 \times L \times (CCR + AR + TR) + CR \times D} \tag{5e}$$

$$UF_{CRoS-NDN} = {}^{CR}/_{(2 \times L \times CCR + TR \times L + D \times (N \times TR + AR + CR \times (FF+1)))} \tag{5f}$$

$$SE_{estrategiaX} = \frac{UF_{estrategiaX}}{UF_{Omniscient}} \tag{6}$$

*Omniscient* is a reference strategy and has the best possible value for *UF*. In *Omniscient* strategy, for each consumer received content packet, there must be one interest packet passing through links from consumer to producer distance, i.e., network diameter distance (*D*).

*Flooding* strategy sends one interest packet in each network link for each consumer received content packet. Thus, *UF* value yields the relation one to number of network links (*L*).

*ARPLike UF* depends on the interest percentage that do not have a FIB match (*FF*). *ARPLike* node forwards straightly to producer interests with FIB match. If interest does not have a FIB match, node floods the interest in its links. The higher is the fraction of directly forwarded interests ($1 - FF$), the closer *ARPLike UF* becomes to *Omniscient UF*. The higher is the fraction of flooded interests ($FF$), the closer *ARPLike UF* becomes to *Flooding UF*.

In *OSPFLike* strategy, the number of interests on the network depends on: the rate of consumer interests *CR*, the rate of periodic content announcements *CCR*, and the number of announced prefixes *PS*. Consumer interest traverse *D* links to reach producer, yielding ($CR \times D$) denominator component. *OSPFLike* strategy floods each prefix announcement on all network links *L*, yielding $PS \times L \times CCR$ denominator component. Consumer received content equals consumer interest request rate *CR* forming *UF* numerator.

*NLSRLike* differs from *OSPFLike* on *UF* denominator component, replacing ($PS \times L \times CCR$) by ($2 \times L \times (CCR + AR + TR)$). *NLSRLike* node does not flood prefix announcements on network, but it monitor its neighbors sending keep alive interest on all links with rate *CCR*. Also, *NLSRLike* takes two interests per link to synchronize new producer prefixes or topology changes between network nodes. Producers announce new prefixes with rate *AR* and topology changes with rate *TR*.

*CRoS-NDN UF* numerator corresponds to consumer received content rate and it equals consumer interest request rate *CR*. *CRoS-NDN UF* denominator takes the following composition: ($2 \times L \times CCR$) component corresponds to node neighbors monitoring interests, ($TR \times L$) component corresponds to controller discovery interest flooding after each topology change, ($D \times N \times TR$) corresponds to all nodes registering in controller after each topology change, ($D \times AR$) corresponds to producers registering available content prefixes on controller with rate *AR*, ($D \times CR \times FF$) corresponds to consumer to controller route request upon consumer interest FIB match failure, ($D \times CR$) corresponds to consumer to producer interests.

In order to compare signaling efficiency between different strategies using a normalized scale, this work defines the metric *SE*, see equation 6. *SE* takes *Omniscient* as *UF* normalizing factor for other strategies, due to *Omniscient* optimal *UF* value.

### B. Trend analysis

*1) Signaling Efficiency:* This section analyzes signaling efficiency trend as a function of extreme values for its parameters. The analysis identifies a particular set of scenarios that demonstrates the impact of network size, the number of content prefixes, and the content request pattern. Table II resumes the scenarios discussed below.

First analyzed scenario considers large networks with restricted diameter, ($L >> D$). Diameter restricted size follows the network design principle to limit end to end delay. *Flooding SE* tends to zero in this scenario.

Second analyzed scenario is a subset of the first. It additionally considers a high fraction of interests with FIB match failure, ($FF \rightarrow 1$). This scenario occurs due to consumers traffic pattern with uncorrelated interest prefixes and a large number of content prefixes. Higher is the diversity of requested content prefixes, higher is the FIB match fail fraction (*FF*). As a consequence, *ARPLike* node recurrently floods interests without FIB match, its behavior approximates to *Flooding* and *ARPLike SE* tends to zero. This analysis considers not

enough node FIB memory to support all content prefixes simultaneously, leading to FIB entry replacement.

Under node unbounded FIB memory assumption and after enough time, *ARPLike* nodes store routes to all prefixes and FIB match failure tends do zero, as in third scenario. In this case, *ARPLike SE* tends to one.

Fourth analyzed scenario is also a subset of the first. It considers the number of content prefixes close to consumer interest rate, ($PS \rightarrow CR$). Additionally, it ties the prefix announcement rate in one to ease the analysis, ($CCR = 1$). In this scenario, *OSPFLike SE* tend to zero. Higher values of *CCR* also lead *OSPFLike SE* to zero.

Second and Fourth scenarios demonstrate *ARPLike* and *OSPFLike* different weaknesses. Both strategies are sensible to the number of available content prefixes, but *OSPFLike SE* tends to zero irrespectively of consumer traffic pattern. This is in opposition to *ARPLike*.

Fifth scenario compares *CRoS-NDN* and *NLSRLike*. This scenario considers no topology changes, ($TR = 0$). Additionally, it considers a high consumer request rate, much higher than the number of network links, ($CR >> L$), and a high prefix announcement rate, close to consumer request rate, ($AR \rightarrow CR$). Under these premises, *NLSRLike SE* tends to zero, and *CRoS-NDN SE* tends to a constant between $1/2$ and $1/3$.

Higher is the number of prefixes *PS*, better is *CRoS-NDN* and *NLSRLike SE* compared to *OSPFLike*. *CRoS-NDN* and *NLSRLike* announce only new prefixes with rate *AR*. This is in opposition to *OSPFLike* that periodically re-announces all prefixes *PS* with rate *CCR*. Albeit smaller *CCR* value reduces signaling overhead, it increases *CDD* delay for *OSPFLike*, *CRoS-NDN*, and *NLSRLike*. *OSPFLike* comparative disadvantage diminishes with the topology change rate growth, *TR*. Moreover, higher is *TR*, better is *NLSRLike SE* compared to *CRoSNDN*. However, the topology change parameter it is not expected to grow as the topology size, the number of prefixes, and the diversity of requested prefixes.

Sixth scenario considers a convergence state with no topology changes, no new prefix announcements, and no FIB match failures. Under these premises, *CRoS-NDN* and *NLSRLike* have equal signaling efficiency.

The analyzed scenarios demonstrate that *CRoS-NDN* has better signaling efficiency under the following set of factors: node limited FIB memory, network size growth, number of content prefix growth, and consumer uncorrelated content prefix request pattern.

*2) Content Delivery Delay:* Content Delivery Delay (*CDD*) depends directly on three parameters: network diameter (*D*), link delay (*LD*), and connectivity check rate (*CCR*). Lower is *CRR*, slower is *CDD* for *OSPFLike*, *NLSRLike* and *CRoS-NDN* strategies. In special, for ($1/CRR >> LD$), *LD* factor becomes negligible. Table III resumes the *CDD* convergence values for each strategy in this scenario.

### C. Simulation

This section evaluates strategy signaling efficiency *SE* and content delivery delay *CDD* performance through simulation.

Table II. TREND ANALYSIS FOR SIGNALING EFFICIENCY

| Scenario | | *SE* |
|---|---|---|
| 1 | $L >> D$ | $Flooding \rightarrow 0$ |
| 2 | $L >> D$, $FF \rightarrow 1$ | $ARPLike \rightarrow 0$ |
| 3 | $L >> D$, $FF \rightarrow 0$ | $ARPLike \rightarrow 1$ |
| 4 | $L >> D$, $CCR = 1$, $PS \rightarrow CR$ | $OSPFLike \rightarrow 0$ |
| 5 | $L >> D$, $CCR = 1$, $AR \rightarrow CR$, $TR = 0$, $CR >> L$ | $NLSRLike \rightarrow 0$ *CRoS-NDN* $\rightarrow 1/(2+FF)$ |
| 6 | $AR = 0$, $TR = 0$, $FF = 0$ | $NLSRLike =$ *CRoS-NDN* |

Table III. *CDD* TREND FOR ($1/CRR >> LD$)

| Strategy | *CDD* |
|---|---|
| *Flooding* | 0 |
| *ARPLike* | 0 |
| *OSPFLike* | $1/CCR$ |
| *NLSRLike* | $2 \times D/CCR$ |
| *CRoS-NDN* | $1/CCR$ |

This work have implemented the analyzed strategies on network simulator ndnSIM [7].

For each simulated scenario, the work presents *SE* temporal evolution curves. *SE* convergence time gives an indirect measure of *CDD* delay. In order to smooth the curves and to ease readability, *SE* calculus uses 200 seconds average values of total packet amount. All plots have 95 % confidence interval error bar.

Each simulation varies one parameter at time. When not stated in opposition, simulation default parameters use fifty content prefixex ($PS = 50$), prefix announcement rate ($AR = 20$), connectivity check rate ($CRR = 0.01$), consumer interest rate ($CR = 20$), and FIB match failure fraction ($FF = 0.1$). It is worth noting that *CRoS-NDN* and *NLSRLike* announce each producer prefix only once with prefix rate *AR*, while *OSPFLike* periodically announces all prefixes *PS* with interval ($1/CCR$). Simulation limits node FIB size in 40 prefix entries

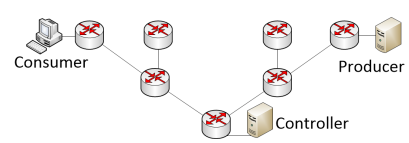



Figure 1. Small tree topology ($L \approx D$): 7 nodes and 6 links.

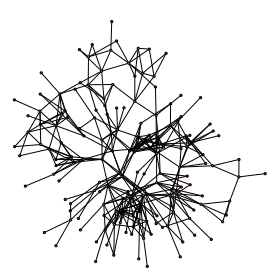
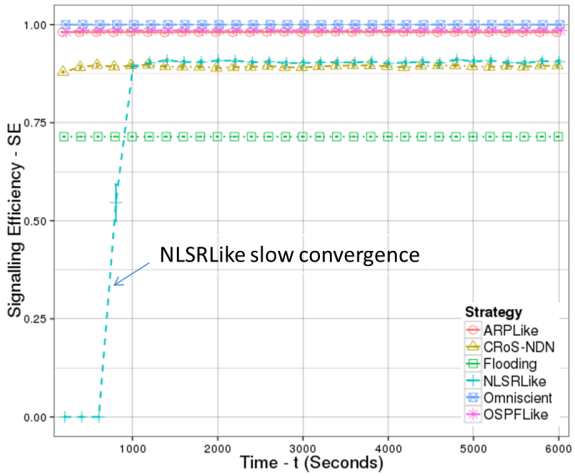
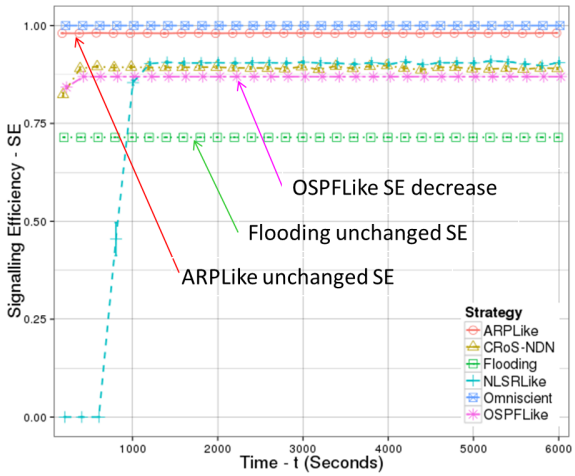


Figure 2. ISP Internet like topology ($L >> D$): 163 nodes and 300 links.

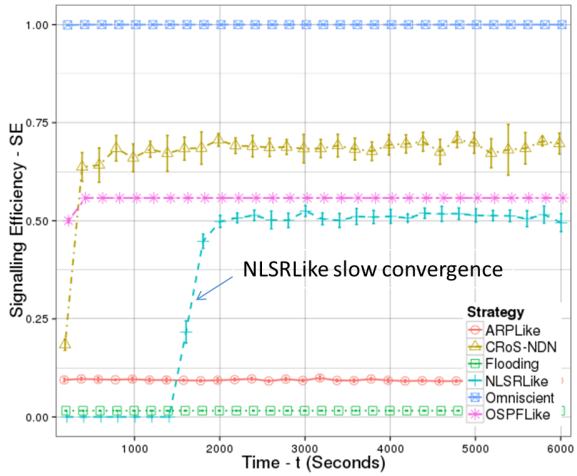



(a) Small tree topology *SE* evolution. Prefix amount $PS = 50$.

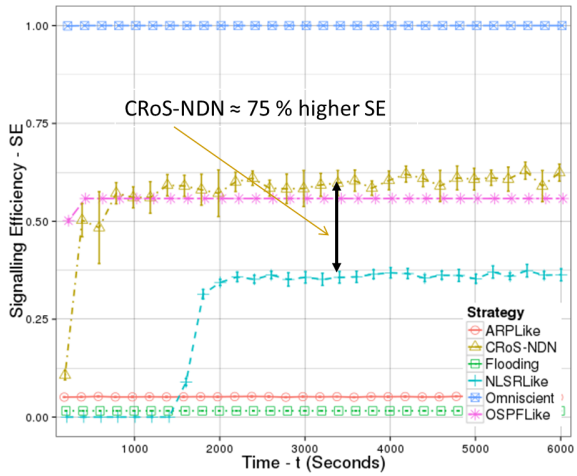



(b) Small tree topology *SE* evolution. Prefix amount $PS = 500$

Figure 3. *SE* variation with the content prefix amount increase from Figure (a) to Figure (b). *OSPFLike SE* highest decrease. *NLSRLike* slowest *SE* convergence. *Flooding* and *ARPLike* unchanged *SE*.




(a) ISP topology *SE* evolution. FIB match fail fraction $FF = 0.05$.




(b) ISP topology *SE* evolution. FIB match fail fraction $FF = 0.1$.

Figure 4. *SE* decrease with the FIB match fail fraction increase from Figure (a) to Figure (b), except for *Flooding* and *OSPFLike* unbounded FIB.

for all strategies, except *OSPFLike* that does not work under FIB constrains.

*1) Content Prefixes Number Effect:* First simulation scenario compares strategy performance variation with the number of content prefixes. It uses the small tree topology from Figure 1. Figure 3 presents *SE* temporal evolution in two scenarios. First one uses 50 content prefixes and the second uses 500 prefixes.

*OSPFLike SE* diminishes in proportion to content prefix amount increase. *NLSRLike* presents the slowest convergence delay. *Flooding* and *ARPLike SE* do not change with prefix amount variation.

*2) Consumer Traffic Pattern Effect:* Second simulation scenario compares strategy performance variation with consumer traffic pattern. It uses the Ebone Internet Service Provider (ISP) topology, Figure 2, extracted from [8]. Figure 4 shows *SE* temporal evolution for two FIB match failure fraction values: $FF = 0.05$ in Figure 4(a) and $FF = 0.1$ in figure 4(b). *CRoS-NDN, NLSRLike*, and *ARPLike SE* decreases with FIB match failure increase. *NLSRLike* presents the slowest *SE* convergence in both cases. *OSPFLike* has unlimited FIB size and its *SE* value does not change. *Flooding* strategy also remains unchanged.

*3) Topology Size Effect:* Third simulation scenario compares strategy performance under different network topologies. Simulations in Figures 4(b) and 3(a) use the same parameters, but the first one uses small tree topology and the second uses ISP topology.

*CRoS-NDN* presents the highest *SE* in the large topology, 75 % higher than *NLSRLike*. Although *Flooding*, *ARPLike*, and *OSPFLike SE* presents good performance in the small topology, these strategies present a significant decrease with topology size increase. *CRoS-NDN* and *NLSRLike SE* present a lower decrease. Additionally, *NLSRLike* presents the slowest *CDD* delay, and this delay increases with topology size to more than 1000 seconds.

## IV. Related Work

CCN original routing strategy announces content name prefixes in the network, like OSPF does for network prefixes in IP.

However, this strategy floods the network with unaggregated prefix updates, posing strong limitations to the number of prefixes and content mobility [9]. NLSR proposal [4] replaces flooding with a hop by hop database synchronizing scheme to disseminate routing information. Although NLSR avoids recurrent flooding, NLSR efficiency is not well analyzed yet.

OSPF and NLSR proactively announces available content prefix through network. In opposition, proposals [5] and [6] reactively adapts its forwarding tables under data plane feedback. In this approach, network node floods interests without a local FIB match to all its faces and, under content reception, node adds a new FIB entry. Albeit its fast convergence time, reactive strategies signaling efficiency requires a comparative analysis demonstrating flooding impact.

Baid *et al.* proposed scheme maps content prefixes to flat names and these names map to network topological addresses, reducing both memory requirements and control signaling [10]. Likewise, work [11] uses a Domain Name System (DNS) scheme to resolve content names to prefixes attached to network segments according to content mobility. These proposals break the bond between packet content and its content name used to forward packets, what is essential to aggregate requests to the same content.

Yi *et al.* highlights forwarding adaptability in function of data plane feedback and they discuss routing protocol need in CCN networks [12]. Despite the affirmative answer, the authors argue CCN convergence time requirements are lower compared to IP networks. Nevertheless, forwarding tables size requirements are not analyzed.

Software Defined Networks (SDN) proposals employ a controller to install, on demand, in network nodes, packet forwarding rules by flow [13], [14]. SDN splits control plane function, that computes routes, and data plane , that forwards packets. A controller node processes control messages and, therefore, reduces memory and processing power requirements from forwarding nodes. *CRoS-NSN* uses SDN plane separation concept to locate and forward content in CCN. Unlike proposals [15], the current work is not based on IP and OpenFlow infrastructure [16].

## V. Conclusion and Future Work

This work proposes Controller-based Routing Strategy for Named-Data Networking (CRoS-NDN). *CRoS-NDN* uses a node controller to acquire and consolidate network information. This consolidation avoids network recurrent flooding, and it increases signaling efficiency. Besides, the present analysis demonstrates *CRoS-NDN* fast convergence time. The proposal also reuses FIB memory reducing forwarding nodes hardware requirements. It shows up to 75 % better signaling efficiency and more than 1000 seconds faster convergence time compared to the second highest *SE* for constrained memory strategy.

The paper analysis shows proactive routing strategies are sensitive to content prefix amount and network size. It also shows reactive routing strategies are sensitive to uncorrelated prefix request pattern and network size. *CRoS-NDN* brings a better balance between these two extremes approaches.

For future work, we will expand the simulated topologies and traffic patterns. We also intend to test the proposal using CCNx [17] distribution in Future Internet Testbed with Security (FITS) [18].

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