

ndnSIM 2: An updated NDN simulator for NS-3

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Abstract—The fundamental departure of the Named-Data Networking (NDN) communication paradigm from the IP principles requires extensive evaluation through experimentation, and simulation is a necessary tool to enable the experimentation at scale. We released the first version of ndnSIM, an open source NS-3-based NDN simulator, back in June 2012. Since then, ndnSIM has undergone substantial development resulting in ndnSIM 2, the first version of which was released in January 2015. This paper reports the design and features of the updated simulator. The goal of the updated simulator is to match the simulation platform to the latest advancements of NDN research. Therefore, it uses the ndn-cxx library (NDN C++ library with eXperimental eXtensions) and the NDN Forwarding Daemon (NFD) to enable experiments with real code in a simulation environment.

1 INTRODUCTION

Named Data Networking (NDN) [1, 2, 3, 4] represents a fundamental departure from today’s Internet architecture which names the communication endpoints, and aspires to be the successor of the TCP/IP protocol stack. As a result, the various design options in the NDN architecture needs to be evaluated in large-scale experimentation. However, it is infeasible to conduct such experimentation with real-world infrastructure and simulation-based evaluation becomes necessary. The main goal of ndnSIM has always been offering the NDN community a common, user-friendly, and open-source simulation platform based on the NS-3 simulator framework [5].

The first public release of ndnSIM took place in June 2012 [6]. Since then, ndnSIM has become a popular tool used by many researchers around the globe. At the time of this writing, ndnSIM mailing list has over 400 subscribers, and more than 290 papers have been published based on research done using ndnSIM. Since the first ndnSIM release, the NDN team has released an updated version of the protocol, in part featured by the new modular NDN Forwarding Daemon (NFD) [7, 8] and ndn-cxx library (NDN C++ library with eXperimental eXtensions) [9] that supports NFD implementation and is used in other C++ based applications.

The goal of this new ndnSIM release is to match the simulation platform to the latest advancements of NDN research and consolidate the code development efforts: the core of ndnSIM is now fully powered by NFD and ndn-cxx code with a few minor updates. With this change, the ndnSIM 2 offers the highest fidelity of the simulation results, as well as allow simple transfer of simulation experiments to the real world and vice versa. To summarize, ndnSIM 2 has

the following major enhancements and features compared to the first release:

- All NDN forwarding and management is implemented directly using the source code of NFD and ndn-cxx.
- The packet format changed to the latest NDN packet format [9].
- Real applications written against the ndn-cxx library can be adapted to run inside the simulated environment.

This version of the simulator, just like the previous one, is implemented in a modular way using different C++ classes to model the behavior of each NDN entity: Faces to communicate with local applications and other simulated nodes, NFD’s Forwarding Information Table (FIB), Pending Interest Table (PIT) and Contest Store (CS), etc. This modular structure allows the easy modification or replacement of any component with no or minimal impact on the other components. In addition, the new release provides a more extensive collection of interfaces and helpers to perform detailed tracing of every component, as well as of the NDN traffic flow.

In order to improve the user experience even more, we encourage the community to provide us valuable feedback by submitting bug reports. We also welcome requests for new feature development.¹ More information about the simulator, basic examples, and tutorials are available on the ndnSIM website: <http://www.ndnsim.net/>.

2 DESIGN

The design for ndnSIM 2 has been directed by our aim to achieve full integration with Named Data Networking Forwarder (NFD) [7, 8]. In this section, we present the overall design of ndnSIM and demonstrate its main structural components and the way that they interact with each other.

2.1 Design summary

ndnSIM 2 provides integration with NFD, while it also allows the simulation of applications written against the cxx library. In this way, ndnSIM offers an integrated simulation environment for researchers and developers to deploy and evaluate their real-world applications at large-scale.

¹. Bug reports and feature recommendations can be submitted on the NDN project issue tracking system website: <http://redmine.named-data.net/projects/ndnsim>

TABLE 1: Comparison among the components of ndnSIM 2 and ndnSIM 1.0

| Component of ndnSIM 2 | Component existed in ndnSIM 1.0? | Features/Design principles inherited from ndnSIM 1.0 | Features/Design changes introduced in ndnSIM 2 |
|---------------------------|------------------------------------|--|---|
| ndn::L3Protocol | Yes | The core component of ndnSIM | NFD integration |
| nfd::Forwarder | Existed as ndn::ForwardingStrategy | – | As a result of integration with NFD, packet forwarding is split into forwarding pipelines and forwarding strategy decisions |
| nfd::face::LinkService | Existed as ndn::Face | Base class for ndn::AppLinkService and ndn::NetDeviceLinkService | Link service abstraction of a nfd::Face implemented by NFD |
| ndn::AppLinkService | Existed as ndn::AppFace | Enables communication with applications | Realization of nfd::face::LinkService abstraction |
| ndn::NetDeviceLinkService | Existed as ndn::NetDeviceFace | Enables communication with other simulated nodes | Realization of nfd::face::LinkService abstraction |
| ::ndn::Face | No | – | Enables the simulation of real applications written against the ndn-cxx library |
| ndn::cs | Yes | Same design | NFD integration |
| nfd::Cs | Existed as ndn::cs | – | 1) Interest selectors handling 2) Not yet flexible to cache policies |
| nfd::Pit | Existed as ndn::pit | – | Abstraction implemented by NFD |
| nfd::Fib | Existed as ndn::fib | – | Abstraction implemented by NFD |
| nfd::fw::Strategy | Existed as ndn::ForwardingStrategy | – | 1) Per namespace strategy 2) Different built-in strategies |
| Applications | Yes | Equivalent functionality | Use of the ndn-cxx library |
| Trace helpers | Yes | Equivalent functionality | Directly trace events from NFD |

As a result of the NFD integration, the installation of the NDN protocol stack (ndn::L3Protocol) on a simulated node results in creating of NFD instance and associating it with the node. The code used for any experiments with NDN forwarding (e.g., custom forwarding strategies) can be directly used inside ndnSIM and vice versa. Moreover, the ability to select different forwarding strategies for different namespaces, the full-featured support for Interest selectors and crypto operations, and the use of the full-featured NDN packet format ensure that the simulations are maximally realistic. With the added features, ndnSIM 2 has increased memory and CPU requirements compared to ndnSIM 1.0, but still allowing a large scale simulations on general-purpose hardware. The memory overhead per CS and PIT entry is presented in Table 2. ndnSIM 1.0 can process approximately 53K packets (Interest and Data) per wall clock second, while ndnSIM 2 can process approximately 17K packets (Interest and Data) per wall clock second.

ndnSIM’s NDN stack is implemented as a network-layer protocol model and can run on top of any available link-layer protocol model (point-to-point, CSMA, wireless, etc.). In addition to that, the simulator provides an extensive collection of helpers (NDN Stack, Application, FIB, Global Routing, Link Control, and Strategy Choice helpers) and tracers (packet-level, application-level, content store) to perform detailed tracing behavior of every component, as well as NDN traffic flow.

The basic components of this ndnSIM release are shown in Figure 1 and a comparison among their design principles and features for the new and the previous release of the simulator is presented in Table 1. These components are also listed below:

- **ndn::L3Protocol**: NS-3 abstraction of the NDN stack implementation. Its main task is initialization of the NFD instance of each node that participates in the simulation scenario and provides tracing sources to measure NDN performance (sent/received interest and data, satisfied/unsatisfied interests).
- **NFD**: implementation of the Named Data Networking Forwarding Daemon, including:

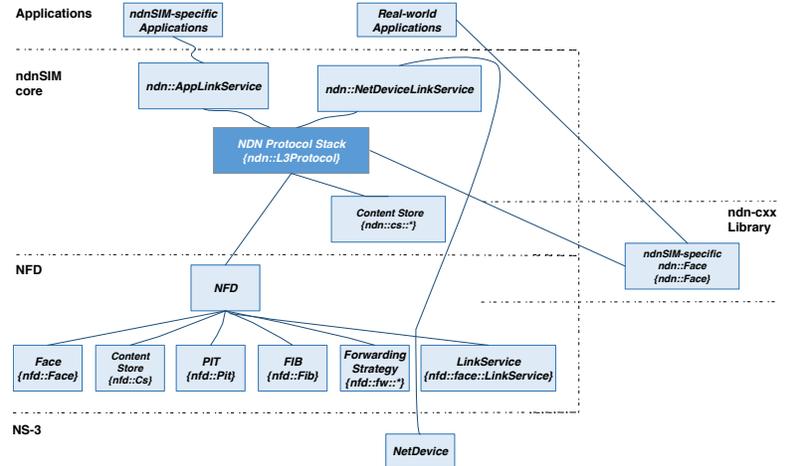


Fig. 1: Structural diagram of the ndnSIM design components

- **nfd::Forwarder**: main class of NFD, which owns all faces and tables of the NDN router node and implements NDN forwarding pipelines.
- **nfd::Face**: NFD Face abstraction that implements the required communication primitives to actually send and receive Interest and Data packets.
- **nfd::face::LinkService**: base class of NFD LinkService abstraction. LinkService translates between network layer packets (Interests, Data, and Nacks) and link layer packets (TLV blocks).
- **nfd::face::Transport**: base class of NFD Transport abstraction. Transport provides best-effort packet delivery service to the link service of a face.
- **nfd::Cs**: the cache of Data packets that is used by NFD. The current release of ndnSIM also includes the old **ndn::ContentStore** abstraction (see below) ported from the previous release to enable richer options for simulation of content store operations (nfd::Cs is not yet as flexible when it comes to cache replacement policies).
- **nfd::Pit**: the Pending Interest Table (PIT) of NFD

TABLE 2: Average memory overhead of ndnSIM 2 and ndnSIM 1.0

| Entry Type | ndnSIM 1.0 | ndnSIM 2 |
|---------------|------------|----------|
| Per CS Entry | 1.3 Kb | 2.8 Kb |
| Per PIT Entry | 0.8 Kb | 5.1 Kb |

keeps track of Interest packets that were forwarded upstream toward one (or more) content source(s). In this way, Data can be sent downstream to one (or more) requester(s).

- **ndf::Fib**: the Forwarding Information Base (FIB) is used to forward Interest packets toward one (or more) potential source(s).
- **ndf::fw::Strategy**: the forwarding strategy in NFD makes the decisions regarding whether, when, and where the Interest packets will be forwarded. `ndf::fw::Strategy` is an abstract class that needs to be implemented by all the built-in or custom forwarding strategies.
- **ndf::measurements::Measurements**: the table, where NFD stores measurement information regarding a name prefix. It is used by the forwarding strategies.
- **ndf::strategy choice::StrategyChoice**: this table contains the forwarding strategy selected for each namespace.
- **ndn::AppLinkService**: realization of the `ndf::face::LinkService` abstraction to enable communication with applications.
- **ndn::NetDeviceLinkService**: realization of the `ndf::face::LinkService` abstraction to enable communication with other simulated nodes.
- **ndn::cs::***: the Content Store (CS) structure as implemented in ndnSIM 1.0. It includes a number of replacement policies and, in general, is more flexible than the current CS implementation of NFD.
- **Basic NDN applications**: implementation of built-in NDN consumer and producer applications that can generate and sink NDN traffic. These applications include parameters that can be configured by the user in the simulation scenario and thus generate NDN traffic according to a user-defined pattern.
- **Trace helpers**: a collection of trace helpers that simplify collection and aggregation of various necessary statistical information about the simulation and write this information in text files.
- **ndnSIM helpers**: a collection of helpers, which simplify the configuration of various parameters that will be used during the simulation execution.

We used the `LinkService` abstraction to implement the basic communication principles instead of implementing our own Transport. This is a solution to optimize packet processing and avoid unnecessary memory operations. Through this approach, we also managed to maintain the NS3 packet tags attached to each packet sent/received by a simulated node, which otherwise would be lost.

2.2 Core NDN protocol

The core component of the ndnSIM architecture is `ndn::L3Protocol`. This component serves as a consolidator for the NDN protocol stack and can be installed in each

simulated node in a way similar to other network protocol stacks, such as IPv4 and IPv6. When it is installed on a NS-3 node, it performs the initialization of the NFD instance, creates the necessary NFD managers (`FibManager`, `FaceManager`, `StrategyChoiceManager`), tables (`PIT`, `FIB`, `StrategyChoice`, `Measurements`), and special faces (i.e., `Null Face`, `Internal Face`). In addition to that, the `ndn::L3Protocol` class defines an API to handle the registration of new `ndf::Face` instances to NFD using the `AddFace` method and provides NS-3 `TraceSource` entry points of NDN-level packet tracing.

2.3 Named Data Networking Forwarding Daemon (NFD)

ndnSIM integrates the NFD codebase with a few small adaptations to the simulation environment². In the rest of this section we describe NFD structure and list the major challenges we faced during the integration.

2.3.1 NFD Internal Structure

The basic modules of NFD are the following [7]:

- **ndn-cxx Library, Core, and Tools**, which provides various common services shared between different NFD modules.
- **Faces** that implement communication abstraction on top of various lower level transport mechanisms.
- **Tables**, realizing the Content Store (CS), the Pending Interest Table (PIT), the Forwarding Information Base (FIB), `StrategyChoice`, `Measurements`, and other data structures to support forwarding of NDN Data and Interest packets.
- **Forwarding pipelines**, a series of steps that operate on a packet or a PIT entry. Individual pipelines are triggered by a specific event, such as reception of the Interest, detecting that the received Interest was looped, when an Interest is ready to be forwarded out of the Face, etc.
- **Forwarding strategies**, a decision maker about Interest forwarding, which is attached at the end or beginning of the pipelines.
- **Management**, allowing applications to configure NFD and set/query NFD's internal states.

2.3.2 Challenges of NFD integration

Towards this integration, we had to address the following challenges:

- We had to enable the use of simulation time in NFD. Therefore, we took advantage of the `CustomClock` class provided by the `ndn-cxx` library in order to convert `ndnSIM` time to `system_clock::time_point` and `steady_clock::time_point`.
- The scheduler of NFD was redirected to `ns3::Simulator`, so that NFD can schedule events that will be executed by the simulator.

² Because of these required adaptations, the version of NFD that ndnSIM is based on tends to be slightly behind the latest version of NFD/`ndn-cxx`

- To optimize the signing process used by NFD for the interaction with its managers through its management protocol, we designed a custom keychain that provides high performance (i.e., minor crypto overhead) during the simulation. However, for simulations that need real crypto operations, the use of a full-featured keychain structure can be selected in the simulation scenario.
- The forwarding pipeline of NFD had to be extended with the `beforeSatisfyInterest` and `beforeExpirePendingInterest` signals, so that the tracing of the `SatisfiedInterests` and `TimedOutInterests` events is enabled to the simulator.
- We enabled the configurability of NFD parameters internally using specially designed configuration files to avoid the overhead of parsing raw external files and thus optimize the simulation process.

2.3.3 Face abstraction

It is similar to the corresponding abstraction of the previous `ndnSIM` version. This abstraction (`nfd::Face`) contains the required low-level communication primitives to handle Interest and Data packets. As mentioned in [7], these primitives include functions to send an Interest/Data packet and terminate the communication on a Face.

2.3.4 *ndnSIM* specific `ndn::Face`

The version of `ndn-cxx` library bundled with `ndnSIM` includes a modified version of `ndn::Face` to directly send and receive Interest and Data packets to and from the simulated instances of NFD. With this modification, `ndnSIM` enables support to simulate real NDN applications written against the `ndn-cxx` library. A detailed guide on how to simulate such applications is available on the `ndnSIM` website: <http://ndnsim.net/2.1/guide-to-simulate-real-apps.html>.

2.3.5 LinkService abstraction

A link service of NFD must translate between network layer packets (Interests, Data, and Nacks) and link layer packets (TLV blocks). In `ndnSIM`, we have implemented a special Link Service base class (`ndn::TracingLinkService`), which is used by both the `ndnSIM` applications (`ndn::AppLinkService`) and the layer 2 devices (`ndn::NetDeviceLinkService`).

2.3.6 NFD's Content Store

In the NDN communication model, Content Store offers in-network caching for Data packets. Arriving Data packets are placed in the cache as long as possible, so that to satisfy future Interests that would request the same Data. In this way, the protocol performance is enhanced making NDN robust against packet losses and errors and capable of inherent multi-casting.

As with many other forwarding components, this version of `ndnSIM` uses content store implementation from the NFD codebase. This implementation takes full consideration of Interest selectors, however is not yet flexible when it comes to cache replacement policies. The feature to extend CS flexibility is currently in active development and, for the time being, we have also ported the old `ndnSIM` 1.0 content store to the new code base, which is discussed in 2.6.

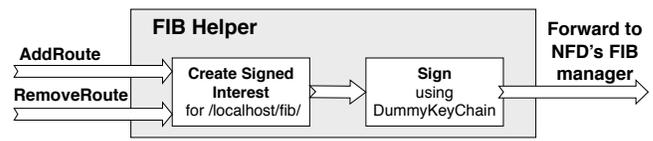


Fig. 2: Operations of the FIB helper

2.3.7 Pending Interest Table (PIT)

In our implementation, the class `nfd::Pit` of NFD is used as the PIT abstraction. PIT maintains the state for the Interest packets that have been forwarded upstream toward one (or more) potential data source(s) of matching Data. It provides directions for the reverse forwarding of the Data packets toward the data consumer(s). In addition to that, PIT also contains recently satisfied Interest packets for the purposes of loop prevention.

For more information about the PIT structure and the operations performed on it, one can refer to [7].

2.3.8 Forwarding Information Base (FIB)

The class `nfd::Fib` of NFD is used as the FIB abstraction. This abstraction is used by the forwarding strategies for Interest forwarding toward potential content source(s). For each Interest that needs to be forwarded, a longest prefix match lookup is performed on the FIB.

The FIB is updated only through the FIB management protocol, which is operated on the NDN forwarder side by the FIB manager. To simplify common operations, we created a FIB helper that, for the high-level FIB operations, prepares special signed Interest commands and sends them towards the FIB manager. Currently, the FIB helper implements two high-level operations (Figure 2):

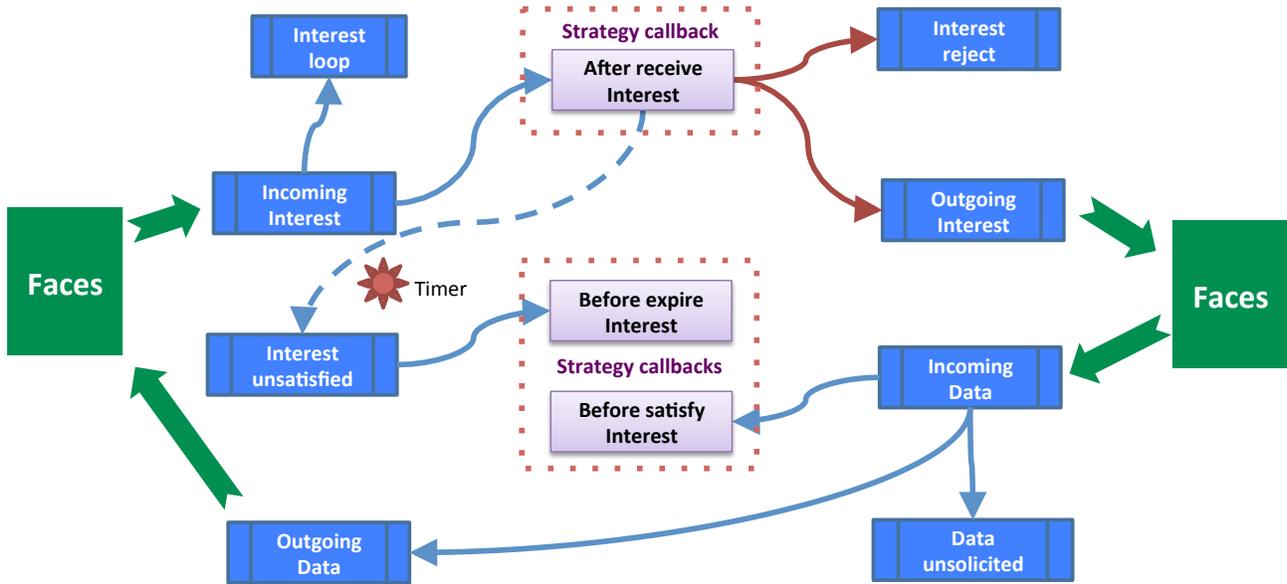
- **AddRoute:** Create a new FIB entry, add a route to the FIB entry, or update the cost of the existing record in the FIB entry.
- **RemoveRoute:** Remove a route record from the FIB entry (a FIB entry with empty `NextHop` records will be automatically deleted).

The Interest commands sent to the FIB manager are signed using the custom key chain mentioned in previous section, which is specially designed to eliminate signing crypto overhead for simulation purposes. If necessary, the full featured crypto support can be re-enabled by switching to the standard `KeyChain` provided by the `ndn-cxx` library.

2.3.9 Forwarding Strategy abstraction

As mentioned before, the forwarding strategy abstraction of NFD makes the decisions regarding the Interest forwarding. That is to say, whether an Interest would be forwarded or not, the upstream face(s), where it would be forwarded, and when it would be forwarded to the selected upstream face(s). `ndnSIM`/NFD features an abstract interface (strategy API) that provides the basic implementation of the forwarding strategies without the need of re-implementing the full Interest processing pipeline. An overview of the forwarding pipeline is presented in Figure 3 and is described in detail in the rest of this section.

The implemented forwarding pipeline allow **pernamespace selection of a specific forwarding strategy**. This



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Fig. 3: Overview of ndnSIM/NFD forwarding pipeline

per-namespace forwarding strategy is registered and maintained at the Strategy Choice table. The Strategy Choice table is updated through the management protocol, operated by the Strategy Choice manager. Similarly to FIB operations, we created a Strategy Choice helper that prepares and sends special signed Interest commands to the manager when strategy selection is requested in the simulation scenario.

The following built-in forwarding strategies are currently available:

- **Broadcast:** Forwards every Interest to all upstream faces.
- **Client Control Strategy:** Allows a local consumer application to choose the outgoing face of each sent Interest packet.
- **Best Route:** Forwards an Interest packet to the upstream face with the lowest routing cost.
- **NCC:** Re-implementation of the CCNx 0.7.2 default strategy.

A new forwarding strategy can implement a completely custom processing or override specific actions in the existing forwarding strategy. The initial step in creating a new strategy is to create a class, say `MyStrategy` that is derived from the `nfd::Strategy` class. This subclass must at least override the triggers that are marked as pure virtual and implement them with the desired strategy logic. It may also override any other available triggers that are marked as just virtual.

If the strategy needs to store information, it is needed to decide whether the information is related to a namespace or an Interest. Information related to a namespace but not specific to an Interest should be stored in Measurements entries; information related to an Interest should be stored in PIT entries, PIT downstream records, or PIT upstream records. After this decision is made, a data structure derived from `StrategyInfo` class needs to be declared. In the existing implementation, such data structures are declared as nested classes as it provides natural grouping and scope protection of the strategy-specific entity, but it is not required to follow

the same model. If timers are needed, `EventId` fields need to be added to such data structure(s).

The final step is to implement at least the “After Receive Interest” trigger and any (or none) of the three other triggers listed below:

- **After Receive Interest:** When an Interest is received, passes necessary checks, and needs to be forwarded, the Incoming Interest pipeline invokes this trigger with the PIT entry, incoming Interest packet, and FIB entry.
- **Before Satisfy Interest:** When a PIT entry is satisfied, before Data is sent to downstream faces (if any), the Incoming Data pipeline invokes this trigger with the PIT entry, the Data packet, and its incoming face.
- **Before Expire Interest:** When a PIT entry expires because it has not been satisfied before all in-records expire, before it is deleted, Interest Unsatisfied pipeline invokes this trigger with the PIT entry.

Actions are the forwarding decisions made by each forwarding strategy and are implemented as non-virtual protected methods of the `nfd::Strategy` class. The provided actions are listed below:

- **Send Interest:** It triggers when entering the Outgoing Interest pipeline.
- **Reject Pending Interest:** It triggers when entering the Interest reject pipeline.

To simplify the operations of specifying the desired per-name prefix forwarding strategy for one, more or all the topology nodes, we provide a Strategy Choice helper that interacts with the Strategy Choice manager of NFD by sending special signed Interest commands to the manager. The operations of this helper are illustrated in Figure 4

2.4 Application Link Service

This class enables the communication of the simulated applications with the NDN network. Specifically, this abstraction provides functions for sending interests, data packets

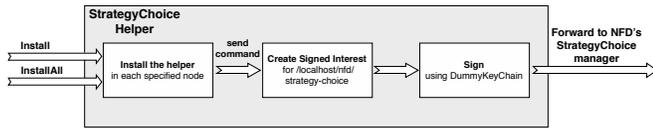


Fig. 4: Operations of the StrategyChoice helper

and NACKs as well as methods to receive packets from the NDN stack. It extends the ndnSIM specific link service class (`ndn::TracingLinkService`). We should note that the wording “send” refers to packets that are sent from the NDN stack and thus are received from the application.

2.5 Network Device Link Service

This component enables the communication between the simulated nodes. Each `ndn::NetDeviceLinkService` instance is permanently associated with a `NetDevice` object and this object cannot be changed for the lifetime of this face. For sending packets between simulated nodes, Interest, Data and NACK packets are converted into the NDN packet format, using routines of the `ndn-cxx` library, and then are encapsulated to a packet instance of NS-3. It extends the ndnSIM specific link service class (`ndn::TracingLinkService`).

2.6 “Old” Content Store

As mentioned above, because of the fact that NFD’s Content Store is not yet flexible when it comes to cache replacement policies, we have also ported the old ndnSIM 1.0 content store implementations to the new code base (Table 3). These implementations feature different cache replacement policies, but have limited support for Interest selectors.

TABLE 3: “Old” Content Store Implementations

| Simple content stores | |
|---|---|
| <code>cs::Lru</code> | Least recently used (LRU) (default) |
| <code>cs::Fifo</code> | First-in-first-Out (FIFO) |
| <code>cs::Lfu</code> | Least frequently used (LFU) |
| <code>cs::Random</code> | Random |
| <code>cs::Nocache</code> | Policy that completely disables caching |
| Content stores with entry lifetime tracking | |
| These policies allow the evaluation of CS entries lifetime (i.e., how long entries stay in CS) | |
| <code>cs::Stats::Lru</code> | Least recently used (LRU) |
| <code>cs::Stats::Fifo</code> | First-In-First-Out (FIFO) |
| <code>cs::Stats::Lfu</code> | Least frequently used (LFU) |
| <code>cs::Stats::Random</code> | Random |
| Content stores respecting freshness field of Data packets | |
| These policies cache Data packets only for the time indicated by <code>FreshnessPeriod</code> . | |
| <code>cs::Freshness::Lru</code> | Least recently used (LRU) |
| <code>cs::Freshness::Fifo</code> | First-In-First-Out (FIFO) |
| <code>cs::Freshness::Lfu</code> | Least frequently used (LFU) |
| <code>cs::Freshness::Random</code> | Random |
| Content store realization that probabilistically accepts data packet into CS (placement policy) | |
| These policies cache Data packets only for the time indicated by <code>FreshnessPeriod</code> . | |
| <code>cs::Probability::Lru</code> | Least recently used (LRU) |
| <code>cs::Probability::Fifo</code> | First-In-First-Out (FIFO) |
| <code>cs::Probability::Lfu</code> | Least frequently used (LFU) |
| <code>cs::Probability::Random</code> | Random |

2.7 Basic NDN applications

The basic applications included in the current ndnSIM release are the same applications that have been included in its previous release with minor changes due to the introduction of the `ndn-cxx` library:

- **ConsumerCbr**: a consumer application that generates Interest traffic according to a user-defined pattern (e.g., predefined frequency, constant rate, constant average rate with inter-Interest gap distributed uniformly at random, exponentially at random, etc.). A user-defined Interest name prefix and sequence number are available. Moreover, this application provides Interest re-transmission according to an RTT-based timeout period similar to the TCP RTO.
- **ConsumerBatches**: a consumer application that generates a specified number of Interest packets at specified time points of the simulation.
- **ConsumerWindow**: a consumer application that generates Interest traffic of variable rate. It implements a simple sliding-window-based Interest generation mechanism.
- **ConsumerZipfMandelbrot**: a consumer application that requests contents (i.e., names in the requests) following the Zipf-Mandelbrot distribution.
- **Producer**: a simple application that sinks Interest traffic and generates Data traffic. Specifically, it responds to each incoming Interest packet with a Data packet that has the same size and name as the corresponding incoming Interest packet.

The interaction of the applications with the core of the simulator is achieved using the `ndn::AppLinkService` realization of the `nfd::face::LinkService` abstraction. The base class `ndn::App` is responsible for the creation/deletion of the `ndn::AppLinkService` instances and their registration in the protocol stack.

2.8 Trace helpers

The trace helpers simplify the collection and aggregation of various necessary statistical information about the simulation and write this information in text files. In our implementation, the capability of tracing events directly from NFD has been added to the tracers. There are three sorts of such helpers:

- **Packet-level trace helpers**: This group includes **L3RateTracer** and **L2Tracer**. The former traces the rate in bytes and in number of packets of Interest/Data packets forwarded by an NDN node, while the latter traces only packets that are dropped on layer 2 (e.g., due to a transmission queue overflow).
- **Content store trace helper**: With the use of `CsTracer`, it is possible to obtain statistics of cache hits/misses on the Content Store of the simulated nodes.
- **Application-level trace helper**: With the use of `AppDelayTracer`, it is possible to obtain data regarding delays between issuing Interest packets and receiving the corresponding Data packet.

3 LIMITATIONS OF CURRENT VERSION AND FUTURE PLAN

Despite the fact that we provide an API to developers in order to simulate real applications using ndnSIM, these applications have to satisfy certain requirements. These requirements are primarily posed by the different logic between real and simulated apps (as they need to be implemented in NS3 and ndnSIM). A detailed list of those requirements is available on our website: <http://ndnsim.net/guide-to-simulate-real-apps.html#requirements>.

NFD versions 0.4 and above handle and process NACKs and, thus, support NDNLv2. In this version, ndnSIM does not support NDNLv2 and, as a result, cannot be yet used to simulate network-level NACKs across simulated nodes. This will be addressed in the next release of ndnSIM.

4 RELATED WORK

Within the recent years, the interest for NDN research has grown. As a consequence, the development of common and handy ways for the evaluation of the proposed NDN research approaches has been absolutely necessary.

One of the first and popular approaches towards that goal is the previous version of ndnSIM [6]. This version, exactly like the current one, is implemented in a modular way and was optimized for simulation purposes. However, the previous version included an independent implementation of NDN packet forwarding and used a deprecated NDN packet format. Moreover, the ndnSIM 1.0 never implemented the full-featured processing of NDN selectors and, as a result, has limitations regarding the accuracy of the simulation results.

Another existing effort is presented by Chiochetti et al. [10, 11]. ccnSim is a scalable chunk-level simulator suitable for the analysis of caching performance of NDN networks. It is developed using the OMNeT++ framework in C++. However, it is mainly optimized for the experimentation on various cache replacement policies for NDN routers and does not provide any flexibility of the forwarding process. As a result, ccnSim cannot be used for the experimentation on a vital core component of the NDN architecture, which is the forwarding strategy layer.

CCN-lite [12] is a lightweight implementation of the CCNx-NDNx protocol. It offers a simulation mode using the OMNeT++ simulation platform. CCN-lite supports scheduling, both at chunk and at packet level, and packet fragmentation. It also supports possible native deployment without any IP layer. However, this effort is mainly intended to run on resource constrained devices and is not optimized to offer high performance as its data structures rely on linked lists.

The Content Centric Networking Packet Level Simulator (CCNPL-Sim) [13] is another NDN simulator developed at Orange Labs. CCNPL-Sim makes use of the Combined Broadcast and Content-Based routing scheme (CBCB) [14] implementation within the SSim simulator to handle event management and name based forwarding and routing. Despite the effectiveness of the SSim simulation scheduler, the mandatory usage of CCNB makes the evaluation of other routing protocols, such as OSPFN [15] and NLSR [16],

impossible thus limiting the experimental scope of this simulator.

Another recently introduced effort is Mini-CCNx [17]. Mini-CCNx is a fork of Mininet-HiFi specially customized to support the emulation of CCNx-NDNx nodes. Its main goal is to add a realistic behavior to the executed tests. Mini-CCNx offers flexibility, because of the Container-Based Emulation features of Mininet, and a simple configuration GUI interface. However, it is based on the packet format of NDNx, which is an outdated version of the NDN communication model. It also mainly focuses on emulating the node hardware instead of the communication model itself.

The affluence of computing resources across the existing research network testbeds/infrastructures (e.g., GENI [18], Open Network Lab (ONL) [19], Emulab [20], etc.) also offers a valuable option for the conduction of real-time research experiments. These testbeds provide both the hardware and the software systems needed by researchers to evaluate their design. However, the complexity that is introduced in order to configure and manage all the delegated resources along with the limited experimental scale are two crucial reasons that lead researchers to resort to simulations.

5 SUMMARY

In this updated simulator, we have focused our efforts on providing a more realistic simulation behavior by integrating the Named Data Networking Forwarding Daemon (NFD) with ndnSIM and using directly the ndn-cxx library and the latest NDN packet format. ndnSIM provides the framework for large-scale experimentation, while its modular design offers the flexibility to the researchers to modify its components with minimal, if any, changes to other parts of its implementation. Detailed information about the current release and additional documentation is available on the ndnSIM website: <http://ndnsim.net>.

We really hope that the NDN community will find ndnSIM a valuable tool and we are looking forward to receiving the community's priceless feedback in order to further improve the simulator.

6 APPENDIX

In this section, we present the revision history of this document.

6.1 Revision History

- **Revision 2 (November 11, 2016):** Updates for ndnSIM 2.1 and 2.2:
 - Added description of the simulation of applications written against the ndn-cxx library and the ndnSIM specific `ndn::Face`.
 - Renamed the `AppFace` and `NetDeviceFace` classes of ndnSIM to `AppLinkService` and `NetDeviceLinkService` and updated the description of each one.
 - Added description on the configurability support of the various parameters of NFD.
 - Updated Table 1 and Figure 1 to add the `nfd::face::LinkService`, `ndn::AppLinkService` and `ndn::NetDeviceLinkService` classes.

- Revised the overall paper to refer to ndnSIM 2 in general instead of ndnSIM 2.0.

- **Revision 1 (January 27, 2015):** Initial release

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