Multipath Forwarding in Named Data Networking: Flow, Fairness, and Context-Awareness

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Abstract. Being a rising architecture for the future Internet, Named Data Networking (NDN) needs adaptive, effective, and efficient forwarding strategies. In this paper, we elicit essential requirements for forwarding strategies and show that existing strategies struggle to fully fulfill these requirements. After that, we investigate how to unlock the full capabilities of NDN by enabling the consideration of context information in the forwarding plane. In this scope, we provide new definitions of NDN sub- and micro-flow. Afterward, we propose a Context-aware Parallel MultiPath forwarding strategy (*CPMP-FS*). The *CPMP-FS* strategy wisely splits NDN flows by determining how the faces will be used while taking into consideration several requirements such as in-network caching, fairness, Interest aggregation, context-awareness, and scalability. We expect *CPMP-FS* to be a step closer to adaptive, effective and efficient forwarding that satisfies both NDN consumers and providers.

1 Introduction

Nowadays Internet is mainly used to distribute and manipulate named information. As a reaction to this shift in Internet usage model from *host-centric* to *data-centric*, a new approach known as Information-Centric Networking (ICN) has emerged. This latter also known as content-aware, or data-oriented networking seeks an Internet architecture with an operation model matching the Internet current and the future usage model by evolving the Internet infrastructure to directly support named data rather than numerically addressed hosts. This approach is being concretized under different projects including but not limited to: Network of Information (NetInf) [13], Content-Centric Networking (CCN) [16], and Named Data Networking (NDN) [42,43]. The focus of this paper is on this latter approach.

NDN [16,42,43] is a future Internet architecture proposal rolling under the ICN paradigm. NDN comes with a new communication model based on four main characteristics:

1. *Receiver-driven data retrieval model*: the user expresses an Interest with a uniquely identified name. The routers use this latter to retrieve the data whose name matches the requested one, and return it to the user;

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2. *Local state information decisions*: they are based on the kept local state information. No global knowledge exists;
3. *Loop free forwarding plane*: a built-in loop prevention mechanism in the forwarding process (maintaining local-state information at each NDN router along with the use of nonces). Thus, neither the Interests nor the data objects can loop for a sufficient period of time;
4. *One-to-one flow balance*: one Interest brings back at most one data object.

The above communication model led to an adaptive forwarding plane. The latter combined with the NDN in-network caching constitute a platform for multipath support called "NDN native multipath support". In this context and in order to benefit of NDN native multipath support, in a previous work [1], we have explained and clarified ambiguities of the inherited definitions of flow and fairness, and we have proposed new definitions in the context of NDN. Furthermore, we have formulated the parallel multipath forwarding packets as an optimization problem and described the initial design of a localized parallel multipath forwarding strategy (*PMP-FS*). Although, this latter shows promising results, serious issues remain open, which is also the case of prominent forwarding strategies as it will be discussed in Sect. 2. Before discussing these issues, it is important to elicit essential requirements for forwarding strategies. Accordingly, we have identified six requirements, namely: flow identification, parallel multipath exploitation, fairness enforcement, flexibility in open networks, and scalability.

Existing forwarding strategies are unable to fully fulfill the aforementioned requirements. This is due, among others, to unrealistic assumptions. For instance, in contrary to existing works, we believe that it is not practical to assume that a requested data packet, with a given name serving different end-users, is related to similar applications. Indeed, a fresh produced data packet of a picture from a disaster scene may be requested by the first-responders application and at the same time by a Facebook application. These requests should not be treated the same way by NDN nodes. In other words, the problem here is how to retrieve the same data with different service classes while ensuring the other requirements.

To tackle this problem, this paper investigates how to unlock the full capabilities of NDN by enabling the consideration of context information in the forwarding plane by building upon our previous work [1]. More specifically, this paper makes the following additional contributions:

- We introduce new definitions of NDN sub- and micro-flow;
- We elicit essential requirements for forwarding strategies and discuss the current NDN literature in regards to these requirements;
- We investigate the enhancement of context-awareness of *PMP-FS*, and propose an advanced context-aware multipath forwarding strategy (*CPMP-FS*). This latter takes into consideration a set of requirements to achieve weighted alpha fairness among different flows.

The remainder of this paper is organized as follows. Section 2 reviews background information and relevant related work. The necessary definitions are grouped in Sect. 3. Section 4 presents an overview of the *PMP-FS* forwarding strategy, while Sect. 5 is devoted to introduce the proposed forwarding strategy *CPMP-FS*. Section 6 concludes the paper and discusses future work.

2 Forwarding in NDN: Requirements *vs.* Reality

In this section, we first present background information on forwarding in NDN. After that, we examine essential requirements for effective forwarding strategies and we sketch our solution for fulfilling these requirements. Finally, we discuss related work and provide a comprehensive qualitative comparison between existing forwarding strategies.

2.1 Background

Forwarding is the process or the action of sending a packet to the preferred next-hop(s) toward a destination based on costs or rankings of faces. In the current Internet based on TCP/IP paradigm, routing plane also referred to as the *control plane* diminished to null the role of forwarding. Indeed, at TCP/IP routers, the forwarding plane also referred to as the *data plane*, has no adaptability. It strictly follows the one choice defined by the routing plane (i.e. the FIB usually has only one next-hop interface to pick). Instead of a native/built-in mechanism for loop prevention in the current network's architecture design, the routing has taken over the responsibilities of loop prevention and the robust data delivery plane solely [38].

By contrast to TCP/IP, NDN loop free forwarding plane is a result of a built-in loop prevention mechanism in the forwarding process (maintaining local-state information at each NDN router). This latter, allows the routing mechanisms to populate each FIB entry with multiple output faces. It also provides the forwarding plane with the flexibility of selecting face(s) for forwarding from multiple eligible available faces [16].

Besides maintaining local-state information at each NDN router, NDN allows the forwarding plane to measure the performance (e.g. Round Trip Time (RTT)) while retrieving data. When multiple next hops exist in a FIB entry, a layer called the *Forwarding Strategy* decides which next hop(s) will be used in forwarding Interests based on routing cost, forwarding plane measurements, and local policies [37]. NDN forwarding decisions are made based first on the route cost corresponding to a *name-prefix* made available by the routing protocol in order to bootstrap the delivery of packets, then utilize the collected local data-plane performance measurements (e.g. RTT, Delay, ...) of each next hop in retrieving data corresponding to *a name-prefix or to the desired granularity* to dynamically update face rankings[1]. Furthermore, the *Forwarding Strategy* based on the latter measurements can detect and recover from packet delivery problems and link

[1] Setting the performance metrics to use and how to use them is the responsibility of each forwarding strategy.

failures locally at the opposite of TCP/IP paradigm were the global convergence of the routing protocol is necessary [37]. In addition, the *Forwarding Strategy* also decides about the unsatisfied Interest retransmission within a specific amount of time. It is responsible of congestion control prevention mechanism, load balance, and fairness policies.

2.2 Forwarding in NDN: Requirements

We believe that for a successful deployment of NDN, the forwarding plane should be able to satisfy several requirements. In the sequel, we enumerate the most important ones and as we go along with the requirements, we present the challenges facing the forwarding strategy developer, and we sketch our solution for fulfilling these requirements.

Flow Identification. TCP/IP paradigm was built on end-to-end communication model. In this model, the source and the destination are known. Packets in the network are tagged by this information. With this legacy, we inherited most of the definitions that we use in nowadays communications and networking community. On the other hand, identifying the end-user's packets in NDN (Interests and data) is meant to be impossible in-between within the network. This is the main difference between NDN and the TCP/IP paradigm caused by the disappearance of end-to-end communication model. The NDN architecture is location-independent. Therefore, the NDN Interests can be forwarded individually and independently and data can be duplicated anywhere and so many times in the network (NDN in-network caching feature). This made the definitions and the rich literature about multipath forwarding strategies, fairness, and congestion control for the TCP/IP architecture no longer appropriate.

From the above discussion, it is clear that the NDN flow should be defined independently of the source and destination of Interests and data. This is still an open issue in the NDN community.

Parallel Multipath Exploitation. This feature can be used to take advantage of the Internet multiplicity in a parallel (simultaneously) or in a sequence manner (serial) as a backup configuration (detect failure and retry alternative paths). NDN native multipath support is used to optimize the efficiency (throughput) on the one hand, and ensures that end-users get a fair share (fairness) on the other hand.

To design a multipath forwarding strategy, besides the definition of the NDN flow, it is mandatory to maintain end-user's fairness and to adopt approaches without relying on RTT measurements.

Fairness. Fairness is a crucial concept in networking that needs complementary information to be understood, since it varies from equality to equity and can be defined in many ways. It has therefore already been the subject of intensive research. Many definitions were given such as Weighted Proportional Fairness [17], Proportional Fairness [21], and the Max-Min Fairness [14]. A unifying mathematical model to fair throughput was first introduced in [22]. The so-called alpha-fair utility functions $U_s(x_s)$ (Eq. 1), which defines the different notions of fairness depending on the choice of a parameter α. This latter is a kind of degree of fairness that controls the trade-off between efficiency and fairness. Please refer to Table 1 for notations.

$$U_s(x_s) = \begin{cases} w_s^{\alpha} \; \frac{x_s^{1-\alpha}}{1-\alpha} \; , & \text{if } \alpha \neq 1 \\ w_s \log(x_s) \; , & \text{if } \alpha = 1 \end{cases} \tag{1}$$

$$\text{for } w > 0, \; \alpha \geq \; 0, \; \text{and } s \in S$$

For example, $\alpha = 0$ with $w = 1$ corresponds to the system maximum efficiency or throughput, $\alpha \rightarrow \infty$ with $w = 1$ corresponds to the Max-Min fairness, and $\alpha = 2$ with $w = \frac{1}{RTT^2}$ corresponds to the TCP fair [20].

Table 1. Notations.

Notation	Meaning
S	Set of flows
s	Individual flow (session)
w_s	Weight of flow (session) s
x_s	Rate of flow (session) s
$U_s(x_s)$	Alpha-fair utility functions
α	A parameter reflecting the fairness

Serving end-users in a fair manner while maximizing network throughput is fundamental and a challenging task in designing a forwarding plane. The TCP/IP paradigm was built on end-to-end communication model where Packets in the network are tagged by the source and destination information. As a consequence, the fairness between end-users is directly related to the fairness between the flows. This is possible thanks to the sharp definition of the flow, which is not the case of NDN.

Flexibility in Open Networks. Ben Abraham and Crowley [7] studied the existing bindings between the application design and the basic or primitive forwarding strategy (as implemented in NFD[2] [3]) and the effect of the assigned

[2] NDN Forwarding Daemon (NFD) is a network forwarder that implements and evolves together with the NDN protocol.

forwarding strategy for a name-space on the application's performance or correctness. Indeed, in a closed environment, the network operator can control the assignment of forwarding strategies to name-spaces but in open networks the local choices could not be guaranteed to be saved.

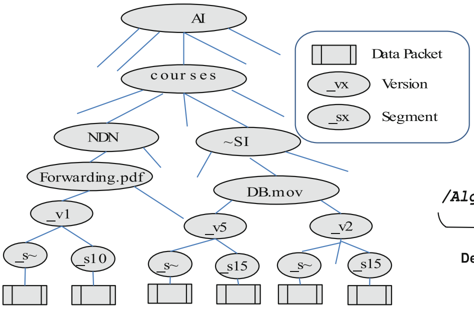
The flexibility of a forwarding strategy in open networks is primordial for application's performance or correctness. In fact, a forwarding strategy should encapsulate different and as many as possible primitive or basic behaviors to serve the same type applications. Thus, the network operator's choice and the assignment of forwarding strategy in the out-of-control networks will not deeply affect the local application's performance.

Context-Awareness. NDN is designed as a common or universal platform for all types of applications (elasticity principal). The requirements of applications are different and they are addressed by the assignment of a strategy to a name-space and by the behavior of the forwarding strategy which includes the decisions about the used next-hop(s), the used performance metrics, and its behavior regarding the unsatisfied Interest (retransmission).

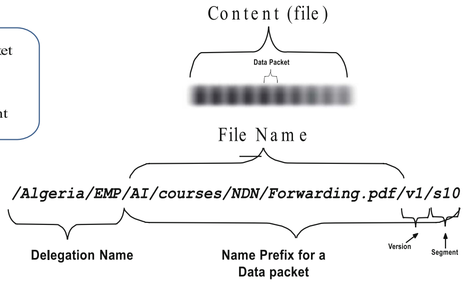
Existing forwarding strategies are unable to fully fulfill the application requirements. The data immutability imposes that the data name does not change in time and in space (storage locations). For instance, a data packet of a critical live stream (e.g. tele-surgery assistance) should not be treated the same way by NDN nodes in time (e.g. stocked for teaching purposes).

Content centricity offered by NDN can address all the application requirements by simply adding the finest possible context to data-names at the time of creation of data. Indeed, NDN imposes no restrictions on names except the hierarchy component structure. The first component for instance can serve as a context component. A byte can be used to define the service-class for the data and time of creation can be used to define the freshness of data. The security certificates can be used to control the announcements of certain service-classes by the eligible producers. We can suffix a context component to the delegation names (a component at the end of the name) indicating the desired treatments and requirements to the core routers.

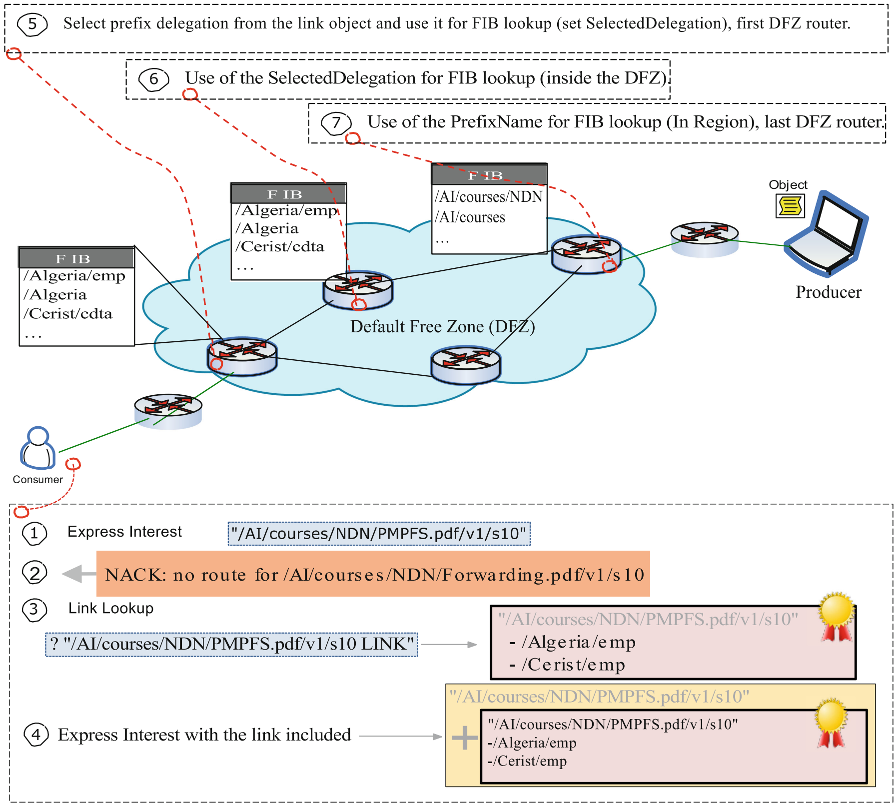
Scalability. NDN names are composed of multiple components (any string of arbitrary length) arranged in a hierarchy, where the slash symbol is the delimiter of components (Fig. 1a and b). Routing scalability was addressed by hierarchical distributed routing through aggregation of routing information. Indeed, NDN FIBs entry contain a name-prefix instead of a complete object name. In addition, NDN FIBs does not and has no need to store two separate FIB entries for example, the name-prefixes /Algeria.dz and /Algeria.dz/emp if they have the same outbound face(s). The latter solution for NDN routing scalability was not satisfactory. Furthermore, it does not resolve producer mobility and (identifier, locator) decoupling.



(a) Naming Hierarchy



(b) Naming a file



(c) Map-and-Encap Mechanism in Action

Fig. 1. Naming in the NDN architecture.

The solution for the aforementioned problems was the adoption of Map-and-Encap approach proposed in [4]. Figure 1c depicts the Map-and-Encap system adopted for NDN [4]:

1. If an Interest with the name: */EMP/courses/NDN/PMPFS.pdf/v1/s10*, is expressed by a consumer, when the first router with no default route finds no route for that prefix in the DFZ FIB, it sends back a NACK. The default-free router based on that un-routable Interest sends a *Network NACK* to the consumer;
2. After receiving the *Network NACK*, the consumer starts the process of discovering of the prefix delegation set by sending an Interest for a link lookup for that name to NDNS (DNS for NDN) [2];
3. When receiving the set of delegation names, it is checked and verified. The consumer re-expresses the Interest but this time carrying the link object (the set of delegation names);
4. The first-default-router selects the best prefix delegation from the link object, set it as default, and uses it for FIB lookup;
5. Within the DFZ, nodes use the "*SelectedDelegation*" for FIB lookup to forward the Interest;
6. When reaching the network edge (producer region (last DFZ router)), the original "*Prefix-Name*" is used for FIB lookup.

From the discussion above, it is clear that a native solution to manage the multitude of application types requirements under the same NDN flow becomes an obligation. In fact, name-prefixes used as a delegation names (global routable prefixes) may embody very distinct name-prefixes[3], hence, different end-users application types. Therefore, a finer granularity is needed than the one provided by the latter delegation name.

As the complexity had to evolve from simplicity [31], a hierarchical structure of behaviors in a forwarding strategy could be adopted to make forwarding strategies flexible in open networks. The former hierarchies have a property of a near-decomposability [31]. By encapsulating different behaviors (service-classes organized in hierarchy) in one forwarding strategy greatly simplifies control of the utilization of resources and the assignment to pre-set finite aggregate service-classes by the network operator will be automatically done. The hierarchy provides structured context and the hierarchical aggregation of class-services ensures scalability, applications correctness, and efficiency. Indeed, a hierarchical structure of behaviors allows the network operator to reduce the aggregate service-classes under each name-space. Thus, keep the utilization of resources under control to fulfill the line speed requirements and fit the available memory capacities.

In this paper, we propose a new forwarding strategy to deal with the above requirements. Before discussing our new strategy, the next subsection reviews existing literature on NDN forwarding strategies in regards to the aforementioned requirements.

[3] Names of Interests forwarded under the same delegation-name are very distinct.

2.3 Related Work

BroadcastStrategy [3] (renamed recently to MulticastStrategy) is the simplest forwarding approach. In this latter, each incoming Interest is forwarded to all available interfaces in FIB entry for the Interest's prefix except the Interest's incoming interface. Another basic strategy is the BestRoute strategy [3] that sends the Interest to the lowest cost face (e.g. RTT, hop count, ...) using the routing protocol assigned cost (e.g. NLSR [15]). As long as that face has the cheapest cost, the strategy keeps sending Interests on it, whether it return the data or not, until the routing protocol deletes the face from the FIB. The authors in [39], proposed a similar strategy dubbed GreenYellowRed. It is an adaptive forwarding that ranks the faces according to their status using a color-coding (Green, Yellow, and Red). Green faces are those returning data, when an interface may or may not return data its marked Yellow, whereas, Red identifies interfaces that do not work.

The NCC strategy [3] (CCN in backward) sends the Interest on one face and waits for a specific prediction time, set by the strategy, for a data packet to be returned. This face is denoted as the "best face" and it is used to forward future Interests with the same name-prefix. The prediction timer is adjusted down upon the reception of requested data on best face and adjusted up whenever the Interest is not satisfied within the predicted time while trying another face. Authors in [10] formulated the problem of joint multipath congestion control and request forwarding as an optimization problem. They proposed the Request Forwarding Algorithm (RFA) strategy as a solution. RFA monitors and extracts the number of corresponding pending Interests of each name-prefix per face. The records are used as weights (a moving average over the reciprocal count of the PIT entries) for the resolution of the optimization problem. The solution is used as the forwarding probabilities of the Interest with a name-prefix over output faces.

In [18], the authors tackled the problem of forwarding with Quality of Service (QoS) in NDN. The main idea of their proposal, *QoS-FS*, is to monitor and estimate, in real-time, bandwidth and RTT of interfaces and use them to determine when and which interface to use to forward an Interest. Chiocchetti et al. [12] proposed *INFORM*, a distributed forwarding strategy based on the Q-routing algorithm. *INFORM* discovers temporary copies of content not addressed in routing tables and forwards requests over the best performing interface at every hop. The best interface was defined as the one with the smallest delivery time.

Authors in [33], proposed an On-demand Multi-Path Interest Forwarding (OMP-IF) strategy. OMP-IF uses only the node disjoint paths to forward Interests simultaneously over multiple paths. The consumer first router uses a weighted round-robin mechanism based on path delays to distribute Interests over multiple faces. In [30], the authors proposed a Multiple Attribute Decision Making (MADM) strategy that supports QoS requirements through the simultaneous use of multiple access networks. MADM extends two existing strategies, the Lowest Cost Strategy (LCS) and Selective Parallel Strategy (SPS). LCS uses three parameters to determine the lowest cost face that satisfies all of the three requirements of an application, which are: (i) a maximum packet loss threshold not to be exceeded, (ii) a maximum delay accepted, and (iii) a minimum bandwidth guaranteed. SPS uses the same parameters as LCS but if one of the requirements is not met, it sends the Interest over multiple faces simultaneously in order to satisfy the specified requirements.

The authors in [26], proposed a Stochastic Adaptive Forwarding (SAF) strategy. SAF sends Interests probabilistically over multiple paths. It uses a feedback mechanism to decrease the traffic over congested links. SAF introduces a virtual face enabling content and context-aware adaptation. A Virtual Interest Packets (VIP) strategy was proposed in [35]. VIP is a framework for joint dynamic forwarding and caching in NDN. It employs a virtual control plane to measure the demand for data. Distributed control algorithms are used to guide caching and forwarding strategies.

As mentioned previously, in a recent work [1], we have proposed a localized parallel multipath forwarding strategy (*PMP-FS*). As we will build upon our previous work, *PMP-FS* will be discussed with more details in Sect. 4.

Table 2 depicts a comprehensive comparison between the aforementioned forwarding strategies. This comparison considers all the above-discussed requirements.

2.4 Motivation

Native context-aware in the forwarding plane enhances QoS/QoE and fulfill the applications requirements as discussed in Sect. 2.2. Despite that, there has been little effort in the area of context-aware forwarding in NDN. Two recent works worth mentioning are Posch et al. [27] and Kim et al. [19].

Posch et al. [27] discussed how to introduce context information in SAF [26]. They proposed to order content classes as follows: VoIP > Video > Data, and introduce a weighting mechanism that enforces this ordering by dropping low-priority content in favor of high-priority content. As discussed above, such an approach is unable to handle important issues such as delegation names (Map-and-Encap adoption) and competition among flows (fairness).

Kim et al. [19] proposed a differentiated services (DiffServ) model for NDN. By following the DiffServ model of the current Internet, the authors propose two differentiated models one at the forwarding plane and the other at the caching plane. The former proposed Differentiated forwarding suffers from several limitations such as flow identification and computation scalability at the edge routers, security risks, and PIT scalability at the core routers. In fact, the proposed control of Interest marking rate algorithm (Algorithm 1 in [19]) suffers from three major limitations:

1. The assumption that a stable RTT can be computed by the NDN routers that monitor the Interests in the PIT does not hold. In fact, the RTT oscillations is the main reason behind the lack of an effective NDN congestion control mechanism as mentioned in [28,29];

Table 2. Comparison between existing forwarding strategies.

Forwarding Strategy	Granularity	Parallel multipath	Fairness	Considered context information	Flexibility in open networks	Target applications	Scalability
Broadcast [3]	Name-space	Yes	No	—	Depend on the sharp choice of the network operators (name-space and strategy)	Loss-sensitive	Yes
BestRoute [3]	Name-space	No	No	Cost of the upstream face (e.g. in terms of hop count)	Depend on the sharp choice of the network operators (name-space and strategy)	Delay-sensitive	Yes
GreenYellow Red [39]	Name-space	No	No	Status of the upstream face	Depend on the sharp choice of the network operators (name-space and strategy)	Loss-sensitive	Yes
NCC [3]	Name-space	Yes	No	Face latency (the time it takes to satisfy an Interest)	Depend on the sharp choice of the network operators (name-space and strategy)	Delay-sensitive	Yes
RFA [10]	Name-space	Yes	No	Current load of a face as indicated by the PIT	Yes	Bandwidth-sensitive	No
INFORM [12]	File	No	No	Delivery times toward other nodes	Depend on the sharp choice of the network operators	Delay-sensitive	Yes
QoS-FS [18]	Name-space	Yes	No	Bandwidth and RTT	Depend on the sharp choice of the network operators (name-space and strategy)	Delay-sensitive Bandwidth-sensitive	Yes
OMP-IF [33]	Name-space	Yes	No	-Path delays -Packet loss	Depend on the sharp choice of the network operators (name-space and strategy)	Delay-sensitive Loss-sensitive	No
MADM [30]	Name-space	Yes	No	Generic (one combination of metrics)	Depend on the sharp choice of the network operators (name-space and strategy)	Many (application requirements trade-off)	No
SAF [26]	Name-space	Yes	No	Generic, considers all available information	Depend on the sharp choice of the network operators (name-space and strategy)	Loss-sensitive	Yes
VIP [35]	Packets	Yes	Yes	Generic, considers all available information	A general framework	All	No
PMP-FS [1]	NDN-flow	Yes	Yes	-Requested throughput (based on the number of Interests and sub-Interests under each name-space) or the desired granularity (Name tree node)) -Cost of every name-space separately -Current load of faces as indicated by the PIT	A general framework	All	Yes

2. In complex scenarios (the presence of cross-traffic with network-intensive workloads) where the flows are competing for the limited resources, the algorithm marks more and more Interests packets, which may lead to:
   – Computation scalability, and thus causing more delay at the edge routers;
   – PITs scalability at core routers. The existing PIT schemes are already a source of scalability concerns [11].
3. Security concerns arise from the marking of Interest packets. In fact, there are two options for marking:
   – Put the marks inside the security envelope, which implies more delay due to the process of embedding self-certification[4] in the Interest packets, or in other words rebuilding the Interest packet;
   – Put the marks outside the security envelope which could be used for a distributed denial-of-service (DDoS) attack.

In this context, we propose to extend our previous work [1] by enabling the consideration of context information natively in the forwarding plane. For this reason, we will follow our recommendations as described in Sect. 2.2.

3 Definitions

To define an NDN flow two questions should be answered:

1. How NDN routers treat names?
2. How NDN routers treat different types of data?

To answer the first question, let us examine the NDN Forwarding Information Base (NDN FIB) functionalities. The NDN FIB entry contains a list of ranked next-hop for specific name prefix. Due to scalability issues [6,23], consensus has not yet been reached on how and what prefix names to populate the FIB. They are a subject of intensive research [4,5,32,41]. All mentioned proposals advocate that NDN packet is forwarded by performing a look-up of its content name using the Longest Prefix Matching (LPM) or the Longest Prefix Classification (LPC). The different Interests with the same routable prefix name issued by different end-users are forwarded under the same FIB name-prefix. Furthermore, the Interests forwarded under the same FIB entry at one router might be forwarded under different FIB entries at another router, and therefore could be forwarded separately.

To answer the second question, we examined the NDN Pending Interest Table (NDN PIT) functionalities. As a core component, PIT is responsible for keeping track of the awaiting Interest packets [39,40]. An Interest is issued by one end-user but it could be aggregated (becoming subsequent Interest) once or many times at the downstream routers. Therefore, for a given router within the network, a pending Interest could be issued by one or many end-users. A returned data object could satisfy one or multiple end-users. The Interest aggregation

[4] Cryptographic mechanism ensuring integrity by binding the prefix-name and data packet content.

feature combined with other features (NDN in-network caching, adaptive forwarding plane, ...) make the power of the NDN architecture. It is important to notice that Interests to be aggregated should have the exact same prefix name and generally this concerns the static content or a Content Delivery Networks (CDN) content. Another aspect to consider is the fact that under the same routable name (prefix-name), we can find a big number of different distinct Interests issued by one or more than one end-user.

From the above discussion, it is clear that defining a flow should be local to the router and for a specific period of time (FIB update). In order to have a clear idea, we model a Router R and its links with its neighbor routers by a weighted directed graph G.

3.1 Router Model

A router R is connected to its K^{ith} neighbor router by a link L_k with capacity C_k, through the corresponding face F_k. The faces of the router R are completely connected to each other with infinite capacity links (Fig. 2a).

We model the router and its direct links as a directed graph $G = (F, L, C)$ (Fig. 2b) where:

- F is a set of vertices (Router faces and a virtual central node R);
- L is the set of edges (Router links);
- C is a function whose domain is L, it is an assignment of capacities to the edges (Router links in terms of inputs and outputs bandwidth);
- The order of graph is $k + 1$ and the size of G is $|L(G)| = 2k$;
- L_{ki} denotes the arc going from F_k to R, represents the downstream through the K^{ith} face F_k, with a capacity C_{ki};
- L_{ko} denote the arc going from R to F_k, represents the upstream through the K^{ith} face F_k, with a capacity C_{ko};

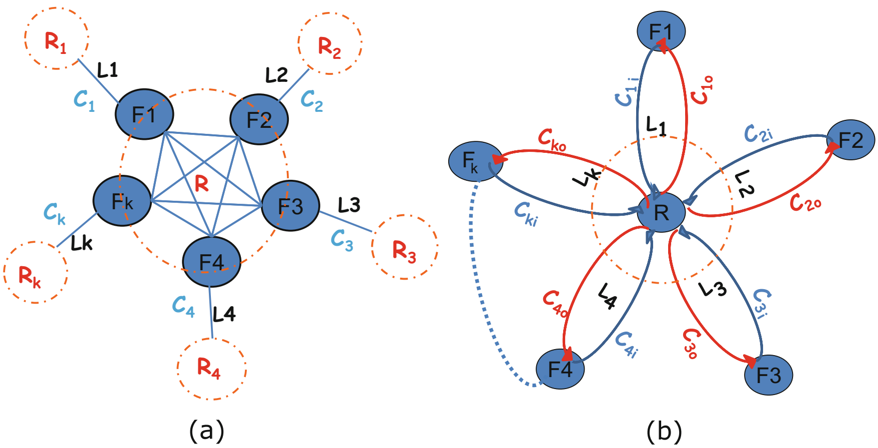


Fig. 2. Router model.

– $C_{ki} + C_{ko} <= C_k$, is the capacity of bidirectional link k connecting the router R and the K^{ith} neighbor router, through the face F_k (Fig. 2).

Definition 1. *A Flow in NDN context is a set of Interests and their corresponding returned data objects forwarded under the same FIB entry proper to a router during a given period. These Interests may have been requested from one or multiple faces and forwarded through one or multiple faces (Fig. 3).*

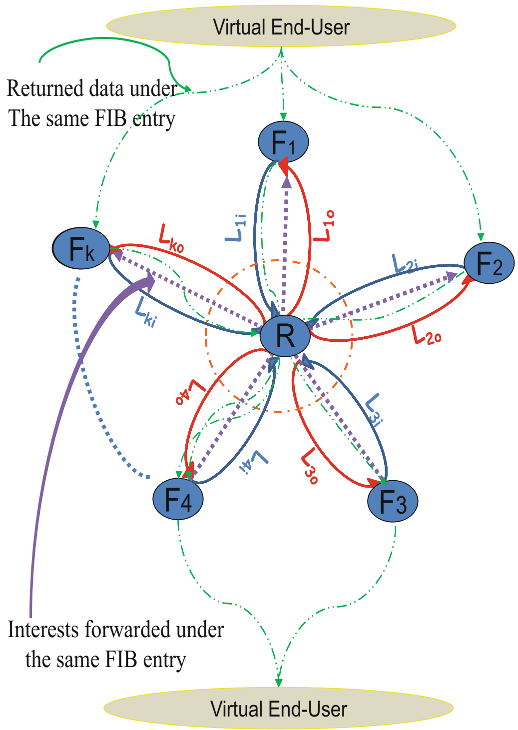


Fig. 3. NDN flow.

Example of NDN Flow. Let us consider an example from Fig. 3. In case the Interests were received from faces F_3 and F_4, the FIB lookup mechanism chooses for them the same FIB entry with the corresponding FIB outgoing faces F_1, F_2 and F_k.

We consider, with analogy to the connected oriented model:

– A virtual end-user source makes connections (max. of six, three in our example) to the other virtual end-user destination;
– The tuple (virtual end-user source, F_3, R, F_2, virtual end-user destination) is a connection;

– If an Interest is forwarded through face F_2 and it is received from face F_3, the Interest will use the resources l_{3i} through R and l_{2o};
– The returned data will follow the reverse path l_{2i} through R and l_{3o}.

This set of Interests and their corresponding returned data objects, are considered for this router as one NDN flow.

Definition 2. *In the presence of competing elastic flows, a Flow Assignment is fair in NDN context if the assignment is weighted alpha-fair, where:*

– *Weights represent the normalized number of distinct awaiting sub-Interests and the answered Interests from the Content Store (CS) as a function of time.*
– *Distinct data object packets sizes and heterogeneous round-trip times ($RTTs$) are taken into consideration.*

3.2 Discussion

The fairness must be addressed across flows, across network and across time [9]. The proposed definition of NDN flow and the fairness criteria does not specify whether many flows can serve a common end-user. We claim in this paper a realistic user-centric conception of fairness. The weighted α-proportional fairness imposed between virtual end-users flows at each node ensures fairness between the real end-users. The notion of friendliness imposed by the emergence of the peer-to-peer networks in the context of TCP/IP paradigm does not need to be addressed in the context of NDN. Taking the definitions above, all the applications and sessions are friendly to each other if the flows are fairly tackled.

In [36], the authors present Fair Interest Limiting (FIL). An NDN version of the fair queuing mechanism used in the TCP/IP paradigm that suffers from the same limitations in terms of fairness [9]. Besides, it does neither take the unpredictable effect of content in-network caching and the Interest aggregation feature nor the distinct data object packets sizes and heterogeneous round-trip times (RTTs) into consideration on the fairness evaluation. At the opposite, weights presented in the above definition come as an answer. The weights must be a function of time to deal with the dynamic nature and unpredictable changes in the network caused by the effect of in-network caching and the Interest aggregation features.

4 PMP-FS Overview

The Parallel Multi-Path Forwarding Strategy (PMP-FS) is a localized strategy that takes advantage of NDN native support of parallel multipath forwarding. In PMP-FS, we formulated the parallel multipath forwarding packets as an optimization problem for Coordinated Multipath Flow Control. The PMP-FS proactively splits traffic by determining how the multiple routes will be used. It takes into consideration the NDN in-network caching and the NDN Interest aggregation features to achieve local weighted alpha fairness among different NDN flows and serves end-users in a fair manner without the need of identifying them while maximizing network throughput. Here, it is significant to mention:

- The requested data objects in NDN may be cached in different locations and in different periods of time by the multi-homing mechanism and/or the NDN in-caching mechanism. The whole data objects may be in one place or dispersed in different places;
- The order of data packets arrival constitutes another difference in forwarding packets between NDN and TCP/IP paradigm. The order of data packets arrival is very important in TCP/IP, which is not the case in NDN. The returned data will be recomposed for application use by end-users;
- Each flow (session) aims at maximizing its throughput;
- Resources are limited: the competition between flows as to be better served by forwarding them to the set of the best possible face(s) is unavoidable;
- Preserving not only fairness between end-users but also efficiency and scalability are a requirement;
- PMP-FS is executed at every NDN router;
- PMP-FS respects the real time (line-speed) constraint;
- PMP-FS takes the effect of content in-network caching mechanism and the subsequent awaiting Interests on the evaluation of fairness;
- Hop-by-hop Interest shaping mechanism to ensure the whole network stability is used;
- We assumed that the flows are elastic, the routing plane is responsible for populating the FIB and we make no assumptions about whether the paths are disjoint.

The PMP-FS splits traffic and achieves fairness in NDN context of the active flows over multiple different faces at each time slot. This increases reliability, robustness, and fault tolerance. The PMP-FS works as follows:

- A hop-by-hop Interest shaping module proposed in [34] is used as a congestion control mechanism. It is executed at every NDN router to ensure the whole network stability. The result of this module is the links input and output capacities between the router at hand and its neighbor routers;
- At every new FIB entry picked: when a router receives an Interest and in case the checking of the CS and the PIT results in a negative response, the FIB is checked and a FIB entry is picked. If the FIB entry has no local measurements (picked for the first time), the PMP-FS qualifies this entry as new.
  - New flow queue is created and set as inactive and the "*after receive Interest*" action is triggered.
  - The first group of Interests (f Interests) of a newly created flow is forwarded immediately. The variation in data object sizes is taken into consideration by the per-flow queuing (counters per flow) and the flow will be considered by the Flow Assignment module only when it is active (the flow queue becomes active when the forwarded Interests bring back data). In this case, we have the estimated size of the data object packets. The latter is smoothly updated at each received data object ("*the before satisfy Interest*" action is triggered).

- Forwarding the first group of Interests of a newly created flow over a set f of faces gives us an opportunity to measure the performance and rank the faces both dynamically and locally (f best faces ranked by the routing plane).
- As an acceptance mechanism the Proportional Integral Controller Enhanced (PIE) is used to drop incoming Interests and send back NACKs based on a probability. Departure rate and the flow queue length are used [25]. When sending NACKs the "*before expire Interest*" action is triggered to update the counters in measurements table.

– At every time slot: this is done in parallel of the receipt of packets and forwarding of Interests.
  1. The PMP-FS collects:
     - The information about the pending and the awaiting Interests with their corresponding FIB entries for each active NDN flow and the Interests that hit the cache. These will be used as weights;
     - The links input and output capacities: the result of the capacities of the hop-by-hop shaping minus the reserved space for the ending sessions (empty flows queues);
  2. The flow assignment module is executed for the active flows. The result is a matrix A of Flow Assignment over the faces. The objective of this module is to perform a controlled splitting of the active flows over the faces while satisfying the limited bandwidth constraints of the outgoing and ingoing router links.
  3. The forwarding decision module: the one-to-one interdependence between Interests and data objects called NDN flow balance propriety gives us the opportunity to carry out a controlled splitting of the flows over the faces by only deciding where and how many Interests of the active flows to forward. Taking as inputs the matrix of Flow Assignment of the last step and the vector of estimated sizes of the active flows data objects, we get the matrix D of the maximum number of Interests to be forwarded for each flow over each face. The matrix D is used to forward the incoming Interests, the next time slot and for every Interest answered another one from the same flow is sent.

– The matrix D is used to forward the incoming Interests and for every Interest answered another one from the same flow is sent.
  The time slot must be chosen in a manner that enable us to integrate the new flows softly and eliminate the RTT variations effect on fairness. We take 25 $msec$ as the time slot which is about the third of mean Internet RTT.

Regarding the performance of PMP-FS, preliminary results are reported and discussed in [1].

5 Best Effort Context-Aware Adaptation: The *CPMP-FS* Strategy

NDN is designed as a common or universal platform for all types of applications (elasticity principle). The requirements of applications are different, some are delay- and loss-tolerant but aim at maximizing the bandwidth, and others are delay-sensitive and require relatively small bandwidth. NDN elasticity must be reflected in the forwarding plane. The latter should aim at achieving the most possible optimal performance for the wide range of application types.

In this section, we investigate the enhancement of context awareness in the PMP-FS forwarding strategy in order to support various types of traffic and their QoS requirements.

5.1 Diagnosis: The Nature of the Challenge

In TCP/IP paradigm, packets of the same flow are implicitly used by the same application. Hence, application requirements have been tackled to a certain point using Intserv and Diffserv approaches [8]. On the other hand, in ICN, the only consistent information that we can use to categorize and classify the packets is the name carried by both Interests and data packets.

In this context, authors in [24] tried to define the CCN flow as "the packets bearing the same object name". This is an ideal definition, if only we do not have unlimited name-space and only if we know the components allocated to object name in the name-prefix. For the sake of clarity, let us assume that we have a limited name-space (very big to support the existing data but limited) and we know the component of each object name (the use of a field in each prefix indicating where the name starts and ends). The resulting over-load from comparing the prefix-name of an incoming Interest, component by component (each component composed of any character type), with the existing prefix-names of the pending Interests will be very high in terms of computation.

Authors in [35] clearly defined the flow through the use of labeling. However, the utilization of labeling constitutes a scalability handicap as mentioned in [29].

In general, the assumption that requested data packets, with a given name serving different end-users, are related to similar type of applications[5] is not realistic. For instance, a produced data packet of a picture from a disaster scene may be requested by the first responder's application and at the same time requested by a Facebook application. These requests should not be treated the same way by NDN nodes. In this work, we do not aim at resolving such a problem, we will tackle it in a future work by considering additive modules while taking into consideration computation scalability and preserving the NDN basis, especially the data immutability and the embedded self-certification. In this paper, we discuss how to enable a native best effort context-awareness at the forwarding plane while considering the aforementioned recommendations sketched in Sect. 2.2.

As a consequence of the adoption of Map-and-Encap [4] approach, with the purpose of scaling NDN routing and resolving producer mobility, a native solution to manage the multitude of application needs under the same NDN flow becomes an obligation. Indeed, name-prefixes used as delegation names (global

[5] Application with the same requirements.

routable prefixes) may embody very distinct name-prefixes, hence, different end-users application types. Therefore, a finer granularity is needed than the one provided by the latter delegation name.

Definition 3. *An NDN sub-flow is a sub-set of Interests and their corresponding returned data of a given NDN flow that need particular forwarding treatment (see Fig. 4). The forwarding strategy specifies the outgoing face(s) ranking (associated measurements (delay, packet loss,...)) and their usage, i.e., how many faces to use and how to send Interests over the chosen faces (multi-cast, send to the best and probe others, ...).*

In this paper, we assume that Interests of the same NDN sub-flow are serving end-users applications with the same requirements. We assume that at the time of creation of data, the first component of the name is a code (a field of one byte) representing a service-class or in other words represents the desired forwarding treatment of the data packet as desired by the producer. The name of data containing the service-class code is inside the security envelope and never changes (immutable name).

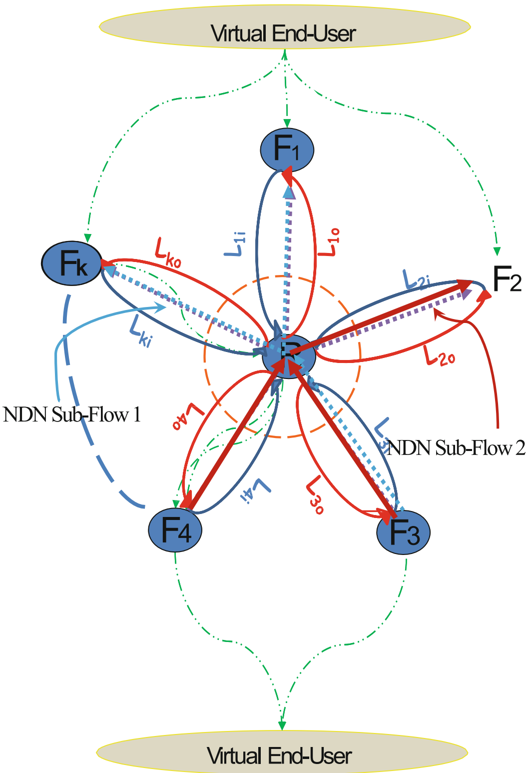


Fig. 4. NDN sub-flow.

5.2 Guiding Policy: Dealing with the Challenge

In this work, we propose a native best effort context-aware scheme providing the best possible QoS/QoE to the end-users. By allowing per-hop management and a simple packet classification in order to control the processing time and storing space according to the computation and storage capabilities of each node. Consequently, the service-class code of each data does not change, it is the assignment to an aggregated service-class at each node that changes. The method used to define equivalent classes and the corresponding code that can be used by the nodes forwarders is outside the scope of this paper and needs more exploration. The six-bit code used by the IP Diffserv can serve as a start point.

The choice of the first name component to carry the service-class code is justified. Indeed, NDN naming schemes can *evolve independently* from the network (NDN imposes no restrictions on names except the component structure). It is worth mentioning that NDN names are opaque to the network and applications may choose the naming scheme that fit their needs. In addition, names are suffixed by components for versions and segmentation of the data (Fig. 1b).

The forwarding strategy should treat the congestion control and the Interest retransmission (local measurements and decisions) on a sub-flow basis. Therefore, we need a finer granularity. For that, we define an NDN micro-flow as:

Definition 4. *An NDN micro-flow is a set of Interests and their corresponding returned data of a given NDN flow. These Interests have been requested from one face (may have multiple in-faces as sub-Interests) and forwarded through one face.*

In Fig. 4, NDN sub-flow 2 is also a micro-flow. The Interest has been requested from face 4 (F4) and forwarded through face 2 (F2). Another Interest with the same name has arrived to the node through face 3 (F3) and has been aggregated in the PIT table waiting to get served by the returned data (general multi-cast). Notice that, the PMP-FS flow assignment module attributes bandwidth at each time slot on a micro-flow basis and the returned data has only one in-face and may have many out-faces.

5.3 Action Plan: Carrying Out the Guiding Policy

In order to manage the sub-flows or in other words, the multitude of applications needs under the same NDN flow (Interests forwarded under the same FIB entry), one has got two choices:

1. Preserve backward compatibility with the existing NFD implementations without any change. The producer propagates the prefixes with different service-classes. For example, the prefix-name "EMP.dz" will be propagated by the routing protocol as many as the types of application requirements ("Code1/EMP.dz", "Code3/EMP.dz", "Code4/EMP.dz", ...). This will be reflected in the FIB table by many FIB-entries (many NDN flows). All the Interests under an NDN flow will be treated by the forwarding strategy in

the same way. In fact, the NDN flow comprises one sub-flow. This solution could raise FIB scalability problems.

2. Change the Longest Prefix Matching (LPM) procedure so that it ignores the first component when performing the matching. In this case, a table called Aggregate Service contains the aggregate services defined by the operator (to reduce the per-sub-flow status managed by each router in order to control processing time and storing space) for each name-prefix (see Fig. 5). Each aggregate service-class represent an NDN sub-flow.

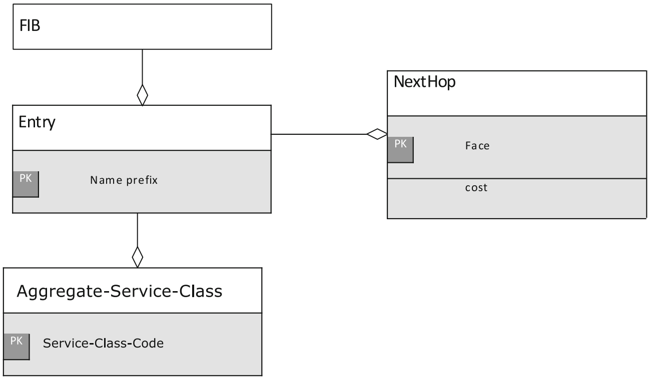


Fig. 5. Aggregate service-class table.

Multipath Utilization. The forwarding strategies implemented in the NFD are in fact special cases of the proposed *CPMP-FS* strategy:

– Best Route Strategy: CPMP-FS with one best link;
– Multi-cast Strategy: CPMP-FS with all upstreams indicated by a FIB entry;
– Client Control Strategy: CPMP-FS testing specific Interests and allowing them to be forwarded to pre-configured outgoing faces.

It is worth pointing out that each one of the mentioned strategies can be considered as a service-class. Therefore, for a name-space, the operator can choose to associate with it one or many sub-service classes.

The flow assignment module performs a controlled splitting of the active flows over the eligible outgoing faces while satisfying the limited bandwidth constraints of the outgoing and ingoing router links. The module defines the share for each micro-flow. The bandwidth of the service-classes under each flow must respect this share.

Congestion Control and Retransmission. The explicit signaling mechanism (NACKs) is used. There is different type of NACKs, representing the reason behind the non-satisfaction of the Interest (congestion, an empty or no forwarding entry at all, upstream face(s) down). The NACK concerns a specific micro-flow unless it is an extreme congestion (upstream face is fully utilized), in this case, the hop-by-hop shaping module is active. Otherwise, NACK may trigger the forwarding strategy to adjust the rate of the micro-flow and to select alternative micro-flow(s) to re-transmit the Interest or *send a NACK only for that micro-flow* (one downstream face).

6 Conclusion and Future Work

In this paper, we shade the light on the essential requirements for adaptive, efficient, and effective NDN forwarding strategies. Existing strategies were discussed in the light of these requirements.

Based on the above, we inferred general guidelines for an adaptive, efficient, and effective forwarding strategy in NDN. Furthermore, we introduced a novel definition for NDN fairness concept. Then, we introduce two new notions related to the NDN flows, namely sub- and micro-flow. Finally, we sketched a Context-aware Parallel MultiPath forwarding strategy (CPMP-FS) that implement the proposed guidelines in order to get a step closer to adaptive, effective and efficient forwarding that satisfies both NDN consumers and providers.

Fully evaluating CPMP-FS is our short-term future work. We also plan to introduce guaranteed QoS based on CPMP-FS (NDiffserv).

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