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Considerations in the Development of a QoS Architecture for CCNx-Like Information-Centric Networking Protocols

Abstract

This is a position paper. It documents the author's personal views on how Quality of Service (QoS) capabilities ought to be accommodated in Information-Centric Networking (ICN) protocols like Content-Centric Networking (CCNx) or Named Data Networking (NDN), which employ flow-balanced Interest/Data exchanges and hop-by-hop forwarding state as their fundamental machinery. It argues that such protocols demand a substantially different approach to QoS from that taken in TCP/IP and proposes specific design patterns to achieve both classification and differentiated QoS treatment on both a flow and aggregate basis. It also considers the effect of caches in addition to memory, CPU, and link bandwidth as resources that should be subject to explicitly unfair resource allocation. The proposed methods are intended to operate purely at the network layer, providing the primitives needed to achieve transport- and higher-layer QoS objectives. It explicitly excludes any discussion of Quality of Experience (QoE), which can only be assessed and controlled at the application layer or above.

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1. Introduction

The TCP/IP protocol suite used on today's Internet has over 30 years of accumulated research and engineering into the provisioning of QoS machinery, employed with varying success in different environments. ICN protocols like NDN [NDN] and CCNx [RFC8569] [RFC8609] have an accumulated ten years of research and very little deployment. We therefore have the opportunity to either recapitulate the approaches taken with TCP/IP (e.g., Intserv [RFC2998] and Diffserv [RFC2474]) or design a new architecture and associated mechanisms aligned with the properties of ICN protocols, which differ substantially from those of TCP/IP. This position paper advocates the latter approach and comprises the author's personal views on how QoS capabilities ought to be accommodated in ICN protocols like CCNx or NDN. Specifically, these protocols differ in fundamental ways from TCP/IP. The important differences are summarized in Table 1:

TCP/IP	CCNx or NDN
Stateless forwarding	Stateful forwarding

Simple packets	Object model with optional caching
Pure datagram model	Request-response model
Asymmetric routing	Symmetric routing
Independent flow directions	Flow balance (see note below)
Flows grouped by IP prefix and port	Flows grouped by name prefix
End-to-end congestion control	Hop-by-hop congestion control

Table 1: Differences between IP and ICN Relevant to QoS Architecture

> Note: Flow balance is a property of NDN and CCNx that ensures one Interest packet provokes a response of no more than one Data packet. Further discussion of the relevance of this to QoS can be found in [FLOWBALANCE].

This document proposes specific design patterns to achieve both flow classification and differentiated QoS treatment for ICN on both a flow and aggregate basis. It also considers the effect of caches in addition to memory, CPU, and link bandwidth as resources that should be subject to explicitly unfair resource allocation. The proposed methods are intended to operate purely at the network layer, providing the primitives needed to achieve both transport and higher-layer QoS objectives. It does not propose detailed protocol machinery to achieve these goals; it leaves these to supplementary specifications, such as [FLOWCLASS] and [DNC-QOS-ICN]. It explicitly excludes any discussion of QoE, which can only be assessed and controlled at the application layer or above.

Much of this document is derived from presentations the author has given at ICNRG meetings over the last few years that are available through the IETF datatracker (see, for example, [Oran2018QoSslides]).

1.1. Applicability Assessment by ICNRG Chairs

QoS in ICN is an important topic with a huge design space. ICNRG has been discussing different specific protocol mechanisms as well as conceptual approaches. This document presents architectural considerations for QoS, leveraging ICN properties instead of merely applying IP-QoS mechanisms, without defining a specific architecture or specific protocol mechanisms yet. However, there is consensus in ICNRG that this document, clarifying the author's views, could inspire such work and should hence be published as a position paper.

2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Background on Quality of Service in Network Protocols

Much of this background material is tutorial and can be simply skipped by readers familiar with the long and checkered history of quality of service in packet networks. Other parts of it are polemical yet serve to illuminate the author's personal biases and technical views.

All networking systems provide some degree of "quality of service" in that they exhibit nonzero utility when offered traffic to carry. In other words, the network is totally useless if it never delivers any of the traffic injected by applications. The term QoS is therefore more correctly applied in a more restricted sense to describe systems that control the allocation of various resources in order to achieve _managed unfairness_. Absent explicit mechanisms to decide which traffic to treat unfairly, most systems try to achieve some form of "fairness" in the allocation of resources, optimizing the overall utility delivered to all traffic under the constraint of available resources. From this, it should be obvious that you cannot use QoS mechanisms to create or otherwise increase resource capacity! In fact, all known QoS schemes have nonzero overhead and hence may (albeit slightly) decrease the total resources available to carry user traffic.

Further, accumulated experience seems to indicate that QoS is helpful in a fairly narrow range of network conditions:

* If your resources are lightly loaded, you don't need it, as neither congestive loss nor substantial queuing delay occurs.

* If your resources are heavily oversubscribed, it doesn't save you. So many users will be unhappy that you are probably not delivering a viable service.

* Failures can rapidly shift your state from the first above to the second, in which case either:

  - Your QoS machinery cannot respond quickly enough to maintain the advertised service quality continuously, or

  - Resource allocations are sufficiently conservative to result in substantial wasted capacity under non-failure conditions.

Nevertheless, though not universally deployed, QoS is advantageous at least for some applications and some network environments. Some examples include:

* Applications with steep utility functions [Shenker2006], such as real-time multimedia

* Applications with safety-critical operational constraints, such as avionics or industrial automation

* Dedicated or tightly managed networks whose economics depend on

strict adherence to challenging service level agreements (SLAs)

Another factor in the design and deployment of QoS is the scalability and scope over which the desired service can be achieved. Here there are two major considerations, one technical, the other economic/political:

* Some signaled QoS schemes, such as the Resource reSerVation Protocol (RSVP) [RFC2205], maintain state in routers for each flow, which scales linearly with the number of flows. For core routers through which pass millions to billions of flows, the memory required is infeasible to provide.

* The Internet is comprised of many minimally cooperating autonomous systems [AS]. There are practically no successful examples of QoS deployments crossing the AS boundaries of multiple service providers. In almost all cases, this limits the applicability of QoS capabilities to be intra-domain.

This document adopts a narrow definition of QoS as _managed unfairness_ (see note below). However, much of the networking literature uses the term more colloquially, applying it to any mechanism that improves overall performance. One could use a different, broader definition of QoS that encompasses optimizing the allocation of network resources across all offered traffic without considering individual users' traffic. A consequence would be the need to cover whether (and how) ICN might result in better overall performance than IP under constant resource conditions, which is a much broader goal than that attempted here. The chosen narrower scope comports with the commonly understood meaning of "QoS" in the research community. Under this scope, and under constant resource constraints, the only way to provide traffic discrimination is in fact to sacrifice fairness. Readers assuming the broader context will find a large class of proven techniques to be ignored. This is intentional. Among these are seamless producer mobility schemes like MAP-Me [Auge2018] and network coding of ICN data as discussed in [NWC-CCN-REQS].

> Note: The term _managed unfairness_ used to explain QoS is generally ascribed to Van Jacobson, who in talks in the late 1990s said, "[The problem we are solving is to] Give 'better' service to some at the expense of giving worse service to others. QoS fantasies to the contrary, it's a zero-sum game. In other words, QoS is _managed unfairness_."

Finally, the relationship between QoS and either accounting or billing is murky. Some schemes can accurately account for resource consumption and ascertain to which user to allocate the usage. Others cannot. While the choice of mechanism may have important practical economic and political consequences for cost and workable business models, this document considers none of those things and discusses QoS only in the context of providing managed unfairness.

For those unfamiliar with ICN protocols, a brief description of how NDN and CCNx operate as a packet network is in Section 3.1. Some further background on congestion control for ICN follows in

Section 3.2.

3.1. Basics on How ICN Protocols like NDN and CCNx Work

The following summarizes the salient features of the NDN and CCNx ICN protocols relevant to congestion control and QoS. Quite extensive tutorial information may be found in a number of places, including material available from [NDNTutorials].

In NDN and CCNx, all protocol interactions operate as a two-way handshake. Named content is requested by a _consumer_ via an _Interest message_ that is routed hop-by-hop through a series of _forwarders_ until it reaches a node that stores the requested data. This can be either the _producer_ of the data or a forwarder holding a cached copy of the requested data. The content matching the name in the Interest message is returned to the requester over the _inverse_ of the path traversed by the corresponding Interest.

Forwarding in CCNx and NDN is _per-packet stateful_. Routing information to select next hop(s) for an Interest is obtained from a _Forwarding Information Base (FIB)_, which is similar in function to the FIB in an IP router except that it holds name prefixes rather than IP address prefixes. Conventionally, a _Longest Name Prefix Match (LNPM)_ is used for lookup, although other algorithms are possible, including controlled flooding and adaptive learning based on prior history.

Each Interest message leaves a trail of "breadcrumbs" as state in each forwarder. This state, held in a data structure known as a _Pending Interest Table (PIT)_, is used to forward the returning Data message to the consumer. Since the PIT constitutes per-packet state, it is therefore a large consumer of memory resources, especially in forwarders carrying high traffic loads over long Round-Trip Time (RTT) paths, and hence plays a substantial role as a QoS-controllable resource in ICN forwarders.

In addition to its role in forwarding Interest messages and returning the corresponding Data messages, an ICN forwarder can also operate as a cache, optionally storing a copy of any Data messages it has seen in a local data structure known as a _Content Store (CS)_. Data in the CS may be returned in response to a matching Interest rather than forwarding the Interest further through the network to the original Producer. Both CCNx and NDN have a variety of ways to configure caching, including mechanisms to avoid both cache pollution and cache poisoning (these are clearly beyond the scope of this brief introduction).

3.2. Congestion Control Basics Relevant to ICN

In any packet network that multiplexes traffic among multiple sources and destinations, congestion control is necessary in order to:

1. Prevent collapse of utility due to overload, where the total offered service declines as load increases, perhaps precipitously, rather than increasing or remaining flat.

2. Avoid starvation of some traffic due to excessive demand by other traffic.

3. Beyond the basic protections against starvation, achieve "fairness" among competing traffic. Two common objective functions are max-min fairness [minmaxfairness] and proportional fairness [proportionalfairness], both of which have been implemented and deployed successfully on packet networks for many years.

Before moving on to QoS, it is useful to consider how congestion control works in NDN or CCNx. Unlike the IP protocol family, which relies exclusively on end-to-end congestion control (e.g., TCP [RFC0793], DCCP [RFC4340], SCTP [RFC4960], and QUIC [RFC9000]), CCNx and NDN can employ hop-by-hop congestion control. There is per-Interest/Data state at every hop of the path, and therefore outstanding Interests provide information that can be used to optimize resource allocation for data returning on the inverse path, such as bandwidth sharing, prioritization, and overload control. In current designs, this allocation is often done using Interest counting. By accepting one Interest packet from a downstream node, this implicitly provides a guarantee (either hard or soft) that there is sufficient bandwidth on the inverse direction of the link to send back one Data packet. A number of congestion control schemes have been developed for ICN that operate in this fashion, for example, [Wang2013], [Mahdian2016], [Song2018], and [Carofiglio2012]. Other schemes, like [Schneider2016], neither count nor police Interests but instead monitor queues using AQM (active queue management) to mark returning Data packets that have experienced congestion. This later class of schemes is similar to those used on IP in the sense that they depend on consumers adequately reducing their rate of Interest injection to avoid Data packet drops due to buffer overflow in forwarders. The former class of schemes is (arguably) more robust against misbehavior by consumers.

Given the stochastic nature of RTTs, and the ubiquity of wireless links and encapsulation tunnels with variable bandwidth, a simple scheme that admits Interests only based on a time-invariant estimate of the returning link bandwidth will perform poorly. However, two characteristics of NDN and CCNx-like protocols can help substantially to improve the accuracy and responsiveness of the bandwidth allocation:

1. RTT is bounded by the inclusion of an _Interest Lifetime_ in each Interest message, which puts an upper bound on the RTT uncertainty for any given Interest/Data exchange. If Interest Lifetimes are kept reasonably short (a few RTTs), the allocation of local forwarder resources do not have to deal with an arbitrarily long tail. One could in fact do a deterministic allocation on this basis, but the result would be highly pessimistic. Nevertheless, having a cutoff does improve the performance of an optimistic allocation scheme.

2. A congestion marking scheme like that used in Explicit Congestion Notification (ECN) can be used to mark returning Data packets if the inverse link starts experiencing long queue occupancy or

other congestion indication. Unlike TCP/IP, where the rate adjustment can only be done end-to-end, this feedback is usable immediately by the downstream ICN forwarder, and the Interest shaping rate is lowered after a single link RTT. This may allow rate adjustment schemes that are less pessimistic than the Additive Increase, Multiplicative Decrease (AIMD) scheme with .5 multiplier that is commonly used on TCP/IP networks. It also allows the rate adjustments to be spread more accurately among the Interest/Data flows traversing a link sending congestion signals.

A useful discussion of these properties and how they demonstrate the advantages of ICN approaches to congestion control can be found in [Carofiglio2016].

4. What Can We Control to Achieve QoS in ICN?

QoS is achieved through managed unfairness in the allocation of resources in network elements, particularly in the routers that forward ICN packets. Hence, the first-order questions are the following: Which resources need to be allocated? How do you ascertain which traffic gets those allocations? In the case of CCNx or NDN, the important network element resources are given in Table 2:

Resource	ICN Usage
Communication link capacity	buffering for queued packets
CS capacity	to hold cached data
Forwarder memory	for the PIT
Compute capacity	for forwarding packets, including the cost of FIB lookups

Table 2: ICN-Related Network Element Resources

For these resources, any QoS scheme has to specify two things:

1. How do you create _equivalence classes_ (a.k.a. flows) of traffic to which different QoS treatments are applied?

2. What are the possible treatments and how are those mapped to the resource allocation algorithms?

Two critical facts of life come into play when designing a QoS scheme. First, the number of equivalence classes that can be simultaneously tracked in a network element is bounded by both memory and processing capacity to do the necessary lookups. One can allow very fine-grained equivalence classes but not be able to employ them globally because of scaling limits of core routers. That means it is wise to either restrict the range of equivalence classes or allow them to be _aggregated_, trading off accuracy in policing traffic against ability to scale.

Second, the flexibility of expressible treatments can be tightly constrained by both protocol encoding and algorithmic limitations. The ability to encode the treatment requests in the protocol can be limited -- as it is for IP where there are only six of the Type of Service (TOS) bits available for Diffserv treatments. However, an equal or more important issue is whether there are practical traffic policing, queuing, and pacing algorithms that can be combined to support a rich set of QoS treatments.

The two considerations above in combination can easily be substantially more expressive than what can be achieved in practice with the available number of queues on real network interfaces or the amount of per-packet computation needed to enqueue or dequeue a packet.

5. How Does This Relate to QoS in TCP/IP?

TCP/IP has fewer resource types to manage than ICN, and in some cases, the allocation methods are simpler, as shown in Table 3:

Resource	IP Relevant	TCP/IP Usage
Communication link capacity	YES	buffering for queued packets
CS capacity	NO	no CS in IP
Forwarder memory	MAYBE	not needed for output-buffered designs (see note below)
Compute capacity	YES	for forwarding packets, but arguably much cheaper than ICN

Table 3: IP-Related Network Element Resources

> Note: In an output-buffered design, all packet buffering resources are associated with the output interfaces, and neither the receiver interface nor the internal forwarding buffers can be over-subscribed. Output-buffered switches or routers are common but not universal, as they generally require an internal speedup factor where forwarding capacity is greater than the sum of the input capacity of the interfaces.

For these resources, IP has specified three fundamental things, as shown in Table 4:

What	How
Equivalence classes	subset+prefix match on IP 5-tuple {SA,DA,SP,DP,PT} SA=Source Address DA=Destination Address SP=Source Port

	DP=Destination Port PT=IP Protocol Type
Diffserv treatments	(very) small number of globally-agreed traffic classes
Intserv treatments	per-flow parameterized _Controlled Load_ and _Guaranteed_ service classes

Table 4: Fundamental Protocol Elements to Achieve QoS for TCP/IP

Equivalence classes for IP can be pairwise, by matching against both source and destination address+port, pure group using only destination address+port, or source-specific multicast with source address+port and destination multicast address+port.

With Intserv, RSVP [RFC2205] carries two data structures: the Flow Specifier (FLOWSPEC) and the Traffic Specifier (TSPEC). The former fulfills the requirement to identify the equivalence class to which the QoS being signaled applies. The latter comprises the desired QoS treatment along with a description of the dynamic character of the traffic (e.g., average bandwidth and delay, peak bandwidth, etc.). Both of these encounter substantial scaling limits, which has meant that Intserv has historically been limited to confined topologies, and/or high-value usages, like traffic engineering.

With Diffserv, the protocol encoding (six bits in the TOS field of the IP header) artificially limits the number of classes one can specify. These are documented in [RFC4594]. Nonetheless, when used with fine-grained equivalence classes, one still runs into limits on the number of queues required.

6. Why Is ICN Different? Can We Do Better?

While one could adopt an approach to QoS that mirrors the extensive experience with TCP/IP, this would, in the author's view, be a mistake. The implementation and deployment of QoS in IP networks has been spotty at best. There are, of course, economic and political reasons as well as technical reasons for these mixed results, but there are several architectural choices in ICN that make it a potentially much better protocol base to enhance with QoS machinery. This section discusses those differences and their consequences.

6.1. Equivalence Class Capabilities

First and foremost, hierarchical names are a much richer basis for specifying equivalence classes than IP 5-tuples. The IP address (or prefix) can only separate traffic by topology to the granularity of hosts and cannot express actual computational instances nor sets of data. Ports give some degree of per-instance demultiplexing, but this tends to be both coarse and ephemeral, while confounding the demultiplexing function with the assignment of QoS treatments to particular subsets of the data. Some degree of finer granularity is possible with IPv6 by exploiting the ability to use up to 64 bits of address for classifying traffic. In fact, the Hybrid Information-

Centric Networking (hICN) project [HICN], while adopting the request-response model of CCNx, uses IPv6 addresses as the available namespace, and IPv6 packets (plus "fake" TCP headers) as the wire format.

Nonetheless, the flexibility of tokenized (i.e., strings treated as opaque tokens), variable length, hierarchical names allows one to directly associate classes of traffic for QoS purposes with the structure of an application namespace. The classification can be as coarse or fine-grained as desired by the application. While not _always_ the case, there is typically a straightforward association between how objects are named and how they are grouped together for common treatment. Examples abound; a number can be conveniently found in [FLOWCLASS].

6.2. Topology Interactions with QoS

In ICN, QoS is not pre-bound to network topology since names are non-topological, unlike unicast IP addresses. This allows QoS to be applied to multi-destination and multipath environments in a straightforward manner, rather than requiring either multicast with coarse class-based scheduling or complex signaling like that in RSVP Traffic Engineering (RSVP-TE) [RFC3209] that is needed to make point-to-multipoint Multiprotocol Label Switching (MPLS) work.

Because of IP's stateless forwarding model, complicated by the ubiquity of asymmetric routes, any flow-based QoS requires state that is decoupled from the actual arrival of traffic and hence must be maintained, at least as soft state, even during quiescent periods. Intserv, for example, requires flow signaling on the order of O(number of flows). ICN, even worst case, requires order of O(number of active Interest/Data exchanges), since state can be instantiated on arrival of an Interest and removed (perhaps lazily) once the data has been returned.

6.3. Specification of QoS Treatments

Unlike Intserv, Diffserv eschews signaling in favor of class-based configuration of resources and queues in network elements. However, Diffserv limits traffic treatments to a few bits taken from the TOS field of IP. No such wire encoding limitations exist for NDN or CCNx, as the protocol is completely TLV (Type-Length-Value) based, and one (or even more than one) new field can be easily defined to carry QoS treatment information.

Therefore, there are greenfield possibilities for more powerful QoS treatment options in ICN. For example, IP has no way to express a QoS treatment like "try hard to deliver reliably, even at the expense of delay or bandwidth". Such a QoS treatment for ICN could invoke native ICN mechanisms, none of which are present in IP, such as the following:

* Retransmitting in-network in response to hop-by-hop errors returned from upstream forwarders

* Trying multiple paths to multiple content sources either in

parallel or serially

* Assigning higher precedence for short-term caching to recover from downstream (see note below) errors

* Coordinating cache utilization with forwarding resources

> Note: _Downstream_ refers to the direction Data messages flow toward the consumer (the issuer of Interests). Conversely, _Upstream_ refers to the direction Interests flow toward the producer of data.

Such mechanisms are typically described in NDN and CCNx as _forwarding strategies_. However, there is little or no guidance for which application actions or protocol machinery a forwarder should use to select the appropriate forwarding strategy for arriving Interest messages. See [BenAbraham2018] for an investigation of these issues. Associating forwarding strategies with the equivalence classes and QoS treatments directly can make them more accessible and useful to implement and deploy.

Stateless forwarding and asymmetric routing in IP limits available state/feedback to manage link resources. In contrast, NDN or CCNx forwarding allows all link resource allocation to occur as part of Interest forwarding, potentially simplifying things considerably. In particular, with symmetric routing, producers have no control over the paths their Data packets traverse; hence, any QoS treatments intended to influence routing paths from producer to consumer will have no effect.

One complication in the handling of ICN QoS treatments is not present in IP and hence worth mentioning. CCNx and NDN both perform _Interest aggregation_ (see Section 2.4.2 of [RFC8569]). If an Interest arrives matching an existing PIT entry, but with a different QoS treatment from an Interest already forwarded, it can be tricky to decide whether to aggregate the Interest or forward it, and how to keep track of the differing QoS treatments for the two Interests. Exploration of the details surrounding these situations is beyond the scope of this document; further discussion can be found for the general case of flow balance and congestion control in [FLOWBALANCE] and specifically for QoS treatments in [DNC-QOS-ICN].

6.4. ICN Forwarding Semantics Effect on QoS

IP has three forwarding semantics, with different QoS needs (Unicast, Anycast, Multicast). ICN has the single forwarding semantic, so any QoS machinery can be uniformly applied across any request/response invocation. This applies whether the forwarder employs dynamic destination routing, multi-destination forwarding with next hops tried serially, multi-destination with next hops used in parallel, or even localized flooding (e.g., directly on Layer 2 multicast mechanisms). Additionally, the pull-based model of ICN avoids a number of thorny multicast QoS problems that IP has (see [Wang2000], [RFC3170], and [Tseng2003]).

The Multi-destination/multipath forwarding model in ICN changes resource allocation needs in a fairly deep way. IP treats all endpoints as open-loop packet sources, whereas NDN and CCNx have strong asymmetry between producers and consumers as packet sources.

6.5. QoS Interactions with Caching

IP has no caching in routers, whereas ICN needs ways to allocate cache resources. Treatments to control caching operation are unlikely to look much like the treatments used to control link resources. NDN and CCNx already have useful cache control directives associated with Data messages. The CCNx controls include the following:

ExpiryTime: time after which a cached Content Object is considered expired and MUST no longer be used to respond to an Interest from a cache.

Recommended Cache Time: time after which the publisher considers the Content Object to be of low value to cache.

See [RFC8569] for the formal definitions.

ICN flow classifiers, such as those in [FLOWCLASS] can be used to achieve soft or hard partitioning (see note below) of cache resources in the CS of an ICN forwarder. For example, cached content for a given equivalence class can be considered _fate shared_ in a cache whereby objects from the same equivalence class can be purged as a group rather than individually. This can recover cache space more quickly and at lower overhead than pure per-object replacement when a cache is under extreme pressure and in danger of thrashing. In addition, since the forwarder remembers the QoS treatment for each pending Interest in its PIT, the above cache controls can be augmented by policy to prefer retention of cached content for some equivalence classes as part of the cache replacement algorithm.

> Note: With hard partitioning, there are dedicated cache resources for each equivalence class (or enumerated list of equivalence classes). With soft partitioning, resources are at least partly shared among the (sets of) equivalence classes of traffic.

7. Strawman Principles for an ICN QoS Architecture

Based on the observations made in the earlier sections, this summary section captures the author's ideas for clear and actionable architectural principles for incorporating QoS machinery into ICN protocols like NDN and CCNx. Hopefully, they can guide further work and focus effort on portions of the giant design space for QoS that have the best trade-offs in terms of flexibility, simplicity, and deployability.

Define equivalence classes using the name hierarchy rather than creating an independent traffic class definition. This directly associates the specification of equivalence classes of traffic with the structure of the application namespace. It can allow hierarchical decomposition of equivalence classes in a natural way because of the way hierarchical ICN names are constructed. Two practical mechanisms are presented in [FLOWCLASS] with different trade-offs between security and the ability to aggregate flows. Either the prefix-based mechanism (the equivalence class component count (EC3) scheme) or the explicit name component-based mechanism (the equivalence class name component type (ECNCT) scheme), or both, could be adopted as the part of the QoS architecture for defining equivalence classes.

Put consumers in control of link and forwarding resource allocation. Base all link buffering and forwarding (both memory and CPU) resource allocations on Interest arrivals. This is attractive because it provides early congestion feedback to consumers and allows scheduling the reverse link direction for carrying the matching data in advance. It makes enforcement of QoS treatments a single-ended (i.e., at the consumer) rather than a double-ended problem and can avoid wasting resources on fetching data that will be dropped when it arrives at a bottleneck link.

Allow producers to influence the allocation of cache resources. Producers want to affect caching decisions in order to do the following:

* Shed load by having Interests served by CSes in forwarders before they reach the producer itself

* Survive transient producer reachability or link outages close to the producer

For caching to be effective, individual Data objects in an equivalence class need to have similar treatment; otherwise, well-known cache-thrashing pathologies due to self-interference emerge. Producers have the most direct control over caching policies through the caching directives in Data messages. It therefore makes sense to put the producer, rather than the consumer or network operator, in charge of specifying these equivalence classes.

See [FLOWCLASS] for specific mechanisms to achieve this.

Allow consumers to influence the allocation of cache resources. Consumers want to affect caching decisions in order to do the following:

* Reduce latency for retrieving data

* Survive transient outages of either a producer or links close to the consumer

Consumers can have indirect control over caching by specifying QoS treatments in their Interests. Consider the following potential QoS treatments by consumers that can drive caching policies:

* A QoS treatment requesting better robustness against transient disconnection can be used by a forwarder close to the consumer (or downstream of an unreliable link) to preferentially cache the corresponding data.

* Conversely, a QoS treatment together with, or in addition to, a request for short latency indicating that the forwarder should only pay attention to the caching preferences of the producer because caching requested data would be ineffective (i.e., new data will be requested shortly).

* A QoS treatment indicating that a mobile consumer will likely incur a mobility event within an RTT (or a few RTTs). Such a treatment would allow a mobile network operator to preferentially cache the data at a forwarder positioned at a _join point_ or _rendezvous point_ of their topology.

Give network operators the ability to match customer SLAs to cache resource availability. Network operators, whether closely tied administratively to producer or consumer, or constituting an independent transit administration, provide the storage resources in the ICN forwarders. Therefore, they are the ultimate arbiters of how the cache resources are managed. In addition to any local policies they may enforce, the cache behavior from the QoS standpoint emerges from the mapping of producer-specified equivalence classes onto cache space availability, including whether cache entries are treated individually or fate-shared. Forwarders also determine the mapping of consumer-specified QoS treatments to the precedence used for retaining Data objects in the cache.

Besides utilizing cache resources to meet the QoS goals of individual producers and consumers, network operators also want to manage their cache resources in order to do the following:

* Ameliorate congestion hotspots by reducing load converging on producers they host on their network

* Improve Interest satisfaction rates by utilizing caches as short-term retransmission buffers to recover from transient producer reachability problems, link errors, or link outages

* Improve both latency and reliability in environments when consumers are mobile in the operator's topology

Rethink how to specify traffic treatments -- don't just copy Diffserv. Some of the Diffserv classes may form a good starting point, as their mappings onto queuing algorithms for managing link buffering are well understood. However, Diffserv alone does not capture more complex QoS treatments, such as:

* Trading off latency against reliability

* Trading off resource usage against delivery probability through controlled flooding or other forwarding mechanisms

* Allocating resources based on rich TSPEC-like traffic descriptions that appear in signaled QoS schemes like Intserv

Here are some examples:

* A "burst" treatment, where an initial Interest gives an aggregate data size to request allocation of link capacity for a large burst of Interest/Data exchanges. The Interest can be rejected at any hop if the resources are not available. Such a treatment can also accommodate Data implosion produced by the discovery procedures of management protocols like [CCNINFO].

* A "reliable" treatment, which affects preference for allocation of PIT space for the Interest and CS space for the Data in order to improve the robustness of IoT data delivery in a constrained environment, as is described in [IOTQOS].

* A "search" treatment, which, within the specified Interest Lifetime, tries many paths either in parallel or serially to potentially many content sources, to maximize the probability that the requested item will be found. This is done at the expense of the extra bandwidth of both forwarding Interests and receiving multiple responses upstream of an aggregation point. The treatment can encode a value expressing trade-offs like breadth-first versus depth-first search, and bounds on the total resource expenditure. Such a treatment would be useful for instrumentation protocols like [ICNTRACEROUTE].

> As an aside, loose latency control (on the order of seconds or tens of milliseconds as opposed milliseconds or microseconds) can be achieved by bounding Interest Lifetime as long as this lifetime machinery is not also used as an application mechanism to provide subscriptions or to establish path traces for producer mobility. See [Krol2018] for a discussion of the network versus application timescale issues in ICN protocols.

7.1. Can Intserv-Like Traffic Control in ICN Provide Richer QoS Semantics?

Basic QoS treatments such as those summarized above may not be adequate to cover the whole range of application utility functions and deployment environments we expect for ICN. While it is true that one does not necessarily need a separate signaling protocol like RSVP given the state carried in the ICN data plane by forwarders, simple QoS treatments applied per Interest/Data exchanges lack some potentially important capabilities. Intserv's richer QoS capabilities may be of value, especially if they can be provided in ICN at lower complexity and protocol overhead than Intserv plus RSVP.

There are three key capabilities missing from Diffserv-like QoS treatments, no matter how sophisticated they may be in describing the desired treatment for a given equivalence class of traffic. Intserv-like QoS provides all of these:

1. The ability to *describe traffic flows* in a mathematically meaningful way. This is done through parameters like average rate, peak rate, and maximum burst size. The parameters are encapsulated in a data structure called a "TSPEC", which can be placed in whatever protocol needs the information (in the case of TCP/IP Intserv, this is RSVP).

2. The ability to perform *admission control*, where the element requesting the QoS treatment can know _before_ introducing traffic whether the network elements have agreed to provide the requested traffic treatment. An important side effect of providing this assurance is that the network elements install state that allows the forwarding and queuing machinery to police and shape the traffic in a way that provides a sufficient degree of _isolation_ from the dynamic behavior of other traffic. Depending on the admission-control mechanism, it may or may not be possible to explicitly release that state when the application no longer needs the QoS treatment.

3. The ability to specify the permissible *degree of divergence* in the actual traffic handling from the requested handling. Intserv provides two choices here: the _controlled load_ service and the _guaranteed_ service. The former allows stochastic deviation equivalent to what one would experience on an unloaded path of a packet network. The latter conforms to the TSPEC deterministically, at the obvious expense of demanding extremely conservative resource allocation.

Given the limited applicability of these capabilities in today's Internet, the author does not take any position as to whether any of these Intserv-like capabilities are needed for ICN to be successful. However, a few things seem important to consider. The following paragraphs speculate about the consequences of incorporating these features into the CCNx or NDN protocol architectures.

Superficially, it would be quite straightforward to accommodate Intserv-equivalent traffic descriptions in CCNx or NDN. One could define a new TLV for the Interest message to carry a TSPEC. A forwarder encountering this, together with a QoS treatment request (e.g., as proposed in Section 6.3), could associate the traffic specification with the corresponding equivalence class derived from the name in the Interest. This would allow the forwarder to create state that not only would apply to the returning Data for that Interest when being queued on the downstream interface but also be maintained as soft state across multiple Interest/Data exchanges to drive policing and shaping algorithms at per-flow granularity. The cost in Interest message overhead would be modest; however, the complications associated with managing different traffic specifications in different Interests for the same equivalence class might be substantial. Of course, all the scalability considerations with maintaining per-flow state also come into play.

Similarly, it would be equally straightforward to have a way to express the degree of divergence capability that Intserv provides through its controlled load and guaranteed service definitions. This could either be packaged with the traffic specification or encoded separately.

In contrast to the above, performing admission control for ICN flows is likely to be just as heavyweight as it is with IP using RSVP. The dynamic multipath, multi-destination forwarding model of ICN makes performing admission control particularly tricky. Just to illustrate:

* Forwarding next-hop selection is not confined to single paths (or a few ECMP equivalent paths) as it is with IP, making it difficult to know where to install state in advance of the arrival of an Interest to forward.

* As with point-to-multipoint complexities when using RSVP for MPLS-TE, state has to be installed to multiple producers over multiple paths before an admission-control algorithm can commit the resources and say "yes" to a consumer needing admission-control capabilities.

* Knowing when to remove admission-control state is difficult in the absence of a heavyweight resource reservation protocol. Soft state timeout may or may not be an adequate answer.

Despite the challenges above, it may be possible to craft an admission-control scheme for ICN that achieves the desired QoS goals of applications without the invention and deployment of a complex, separate admission-control signaling protocol. There have been designs in earlier network architectures that were capable of performing admission control piggybacked on packet transmission.

> The earliest example the author is aware of is [Autonet].

Such a scheme might have the following general shape (*warning:* serious hand-waving follows!):

* In addition to a QoS treatment and a traffic specification, an Interest requesting admission for the corresponding equivalence class would indicate this via a new TLV. It would also need to do the following: (a) indicate an expiration time after which any reserved resources can be released, and (b) indicate that caches be bypassed, so that the admission-control request arrives at a bona fide producer.

* Each forwarder processing the Interest would check for resource availability. If the resources are not available, or the requested service is not feasible, the forwarder would reject the Interest with an admission-control failure. If resources are available, the forwarder would record the traffic specification as described above and forward the Interest.

* If the Interest successfully arrives at a producer, the producer would return the requested Data.

* Upon receiving the matching Data message and if the resources are still available, each on-path forwarder would allocate resources and would mark the admission control TLV as "provisionally approved". Conversely, if the resource reservation fails, the admission control would be marked "failed", although the Data would still be passed downstream.

* Upon the Data message arrival, the consumer would know if admission succeeded or not, and subsequent Interests could rely on the QoS state being in place until either some failure occurs, or

a topology or other forwarding change alters the forwarding path. To deal with this, additional machinery is needed to ensure subsequent Interests for an admitted flow either follow that path or an error is reported. One possibility (also useful in many other contexts), is to employ a _Path Steering_ mechanism, such as the one described in [Moiseenko2017].

8. IANA Considerations

This document has no IANA actions.

9. Security Considerations

There are a few ways in which QoS for ICN interacts with security and privacy issues. Since QoS addresses relationships among traffic rather than the inherent characteristics of traffic, it neither enhances nor degrades the security and privacy properties of the data being carried, as long as the machinery does not alter or otherwise compromise the basic security properties of the associated protocols. The QoS approaches advocated here for ICN can serve to amplify existing threats to network traffic. However:

* An attacker able to manipulate the QoS treatments of traffic can mount a more focused (and potentially more effective) denial-of-service attack by suppressing performance on traffic the attacker is targeting. Since the architecture here assumes QoS treatments are manipulatable hop-by-hop, any on-path adversary can wreak havoc. Note, however, that in basic ICN, an on-path attacker can do this and more by dropping, delaying, or misrouting traffic independent of any particular QoS machinery in use.

* When equivalence classes of traffic are explicitly revealed via either names or other fields in packets, an attacker has yet one more handle to use to discover linkability of multiple requests.

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