On Implicit Denial of Service Attack in NDN and Potential Mitigations

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***Abstract*—One major benefit of named-data networking (NDN) is its potential to control network load by leveraging in-network caching and request aggregation. Both the network operator and consumers benefit from these features, as operating costs are reduced and quality-of-experience is increased.**

However, request aggregation, combined with NDN's loop prevention mechanisms, can create denial-of-service (DoS) against client interests (intentionally and unintentionally) by clients employing multicast forwarding. In this paper, we discuss this problem and propose three increasingly efficient solutions to address the problem; our arguments are backed by simulation and numerical analyses.

***Index Terms*—Information-centric networks; forwarding strategy; DoS attack; request aggregation.**

1. Introduction

One major benefit of named-data networking (NDN) for the future Internet is its potential to help control network load in the face of increasing demand for high-bandwidth content. By leveraging in-network *content caching* and *request aggregation*, NDN helps reduce the number of content packets which transit the network without negatively affecting the consumers. Both the network operator and content consumer benefit from these features, as operating costs are reduced and quality-of-experience (QoE) is increased. The efficacy of both caching and aggregation in reducing network load can be attributed to the fact that most Internet content follows a Zipf popularity distribution [1], [2], and thus a small number of content objects represent the majority of consumers' requests. There have been several efforts, studying the benefits of in-network caching and various approaches to optimizing its performance [3], however request aggregation has not received as much attention from the community.

To review, the main benefit of request aggregation is its reduction of redundant content forwarding through the network core. Request aggregation happens when a router receives an *interest* (request) for a *content object* for which an interest is already pending; instead of redundantly forwarding the interest (and thereafter receiving redundant data), the router aggregates the subsequent interests and satisfies them with the content returned for the original interest. Thus, a significant amount of bandwidth can be saved, particularly in live video streaming applications, where many consumers request the same content simultaneously.

Request aggregation has been identified to come at some cost, namely in information loss to content providers [4]. When consumers' requests are satisfied from caches or by aggregation, the content provider gains no information about the consumer's preference. However, in what follows we investigate a *harmful side-effect* of request aggregation that has been introduced in [5]: a denial-of-service (DoS) vulnerability. Other DoS attacks against NDN have been discussed in the literature [6], however, the authors in [5] have introduced a unique exploit against NDN's request aggregation and loop prevention features, which could be triggered either unintentionally or maliciously by a client employing multicast forwarding. In addition, we propose and evaluate three increasingly-efficient solutions to the problem.

The **contributions** of this paper are: *(i)* A description of this unseen challenge inherent to request aggregation in NDN, which undermines successful content dissemination. *(ii)* A discussion of potential solutions and a discussion of their efficiency and cost. *(iii)* An implementation of the most viable solution and an analysis of its effectiveness through extensive simulation.

In Section 2, we describe the denial-of-service scenario we have identified and discuss situations in which it arises. Then, in Section 3, we propose and evaluate a naive approach to mitigating this attack. We refine our mitigation and present additional analysis in Section 4, and explore additional directions for improvement in Section 5. Finally, we offer concluding remarks in Section 6.

2. Problem Description

We have identified a denial-of-service vector enabled by request aggregation, which is triggered by consumers multicasting interests. This behavior occurs due to NDN's use of nonces for loop detection. Hereafter, we will refer to this unique NDN denial-of-service vector as *iDoS*.

Whenever an NDN application generates an interest, it assigns a random 32-bit integer, called the *nonce*. This nonce is used to determine the uniqueness of an interest, and as mentioned, mitigate forwarding loops in the network. When an NDN router receives a duplicate interest (same interest name and same nonce), it infers that there is a loop, drops the interest, and returns a negative acknowledgment (*NACK*). The NACK

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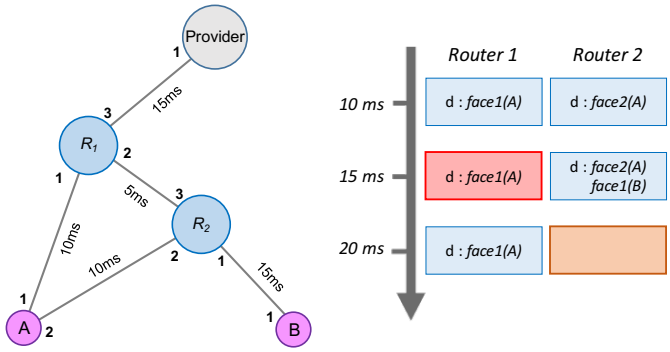


(a) Network topology (b) Routers' PITs in time

Fig. 1: The case study for illustrating the request aggregation process under request broadcasting.

contains a flag indicating the reason for the interest's rejection, which in this case is the *duplicate nonce*.

To illustrate *iDoS*, we will refer to the toy network depicted in Fig. 1(a), composed of a content provider, two routers (R_1 and R_2), and two consumers (A and B). Suppose both A and B request the same content object (d) simultaneously. For clarity, we use the client names A and B to represent the nonces for their respective interests. Consumer A, having two upstream interfaces, utilizes both by multicasting its request.

As shown in Fig. 1(b), at time step 10 ms, R_1 receives a request for d from its *face1* and R_2 receives the same request over its *face2*. At time step 15 ms, R_2 receives a new request for d over *face1*, and aggregates it with the entry it has in its Pending Interest Table (PIT). At the same time, R_1 receives a redundant copy of the same request it received at time 10 ms, this time via *face2*. Since the request has the same content name and nonce, R_1 detects it as a duplicate interest (depicted by the red shaded box in Fig. 1(b)). Due to its detection as a duplicate interest, R_1 drops the interest from *face2* instead of aggregating it with the existing entry, and sends a negative acknowledgment (*NACK*) to the downstream router via *face2*, indicating the receipt of a duplicate nonce. At 20 ms, R_2 receives the duplicate-nonce NACK and removes the PIT entry for the request that it forwarded at time step 10 ms. In this scenario, consumer A receives content d at time 50 ms, while consumer B's request times out despite the availability of d. This timeout occurs because no interest for d was successfully forwarded from R_2 to R_1. The first interest forwarded returned a NACK, and the second was aggregated prior to the receipt of that NACK. Therefore, R_1 will not have forwarded d to R_2.

To generalize this behavior, we define a multicast consumer as any consumer that utilizes more than one upstream interface when sending an interest. One can observe the effect of *iDoS* when *(i)* there is at least one multicast consumer co-located with other consumers, *(ii)* more than one consumer requests the same content object, *(iii)* the additional consumers' requests are aggregated with a PIT entry that has been generated by a multicast consumer, and *(iv)* the multicast consumer's interest is NACKed after the additional interests have been aggregated. It is also necessary that the multicast consumers' request paths converge at some point; this provision will result in identical interests (with the same nonce) arriving at the point of convergence, and thus the generation of a duplicate-nonce NACK.

The *iDoS* attack can be triggered either unintentionally, by an honest multicasting consumer which happens to request the same content as the affected consumer, or intentionally by a malicious user who is capable of guessing which requests a target client will make. The unintentional attack is most likely to arise among consumers of live-streaming video traffic, as in these applications, many consumers concurrently request a content just prior to its generation by the publisher and thus request aggregation is more likely to occur. The real-time nature of live streaming media also makes it more likely for clients to employ multicasting forwarding strategies in order to meet QoE requirements.

Several strategies employing multicasting have been proposed in the literature already [7], [8], [9], [10], [11], however their effects when combined with interest aggregation have not yet been studied. With the exception of [11], which utilizes disjoint paths, all of the above cited forwarding strategies could potentially trigger the outlined DoS scenario. We argue that multicasting strategies, which may be installed on consumer nodes, cannot be safely deployed without augmentation by a multicast-aware forwarding strategy in the network core. Furthermore, even without the use of these strategies, it is possible for a malicious client to multicast interests and cause denial of service regardless; thus either interest aggregation must be disabled, or a mitigation must be employed.

3. Client-Driven Approach

In this section, we discuss a naive approach to mitigating *iDoS*, wherein consumer nodes utilize multiple nonces in order to prevent duplicate-nonce NACKs from being generated.

A. Description of Approach

In the multicast strategy currently available in the reference implementation of NDN, the node sends identical interests with the same nonce on all available faces. We propose a client-driven solution to prevent accidental *iDoS* of other clients in the network, wherein unique nonces are used on all outgoing faces. This strategy is henceforth referred to as Unique Nonce Multicast (*UNM*).

In *UNM*, the client node creates as many nonces as there are available faces, and then forwards the interest with a different nonce on each face. Though the consumer application is typically responsible for nonce generation in standard NDN, we suggest that the generation of additional nonces for *UNM* be handled by the strategy layer. This increases the implementation's flexibility and facilitates compatibility with existing applications, as the application need not be aware of how many faces are available for forwarding. Because unique nonces are used, all of the multicasted interests appear unique to the network and hence no duplicate-nonce NACK will be generated. Because there is no chance of an aggregating interest being NACKed, the *iDoS* scenario is avoided entirely.

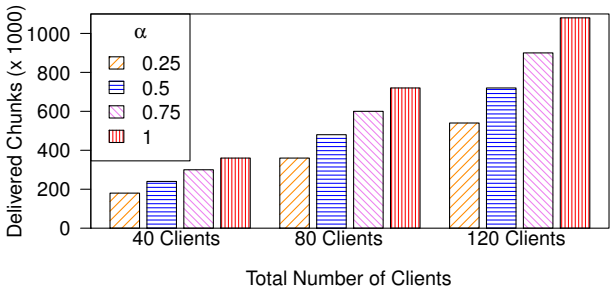


Fig. 2: Total data delivery.

B. Analysis

Even though this approach mitigates *iDoS*, it is not a feasible solution for two reasons. Firstly, it results in significantly increased redundant delivery to the client. Though redundant delivery is possible in any multicast strategy, standard NDN forwarding behavior ensures that if multiple interfaces' interest paths converge, at least one will get NACKed unless it gets aggregated or otherwise dropped before reaching the point of convergence. Under *UNM*, each interest sent by the multicasting consumer is unique, so none will be NACKed and thus (assuming the network is reliable) all will be satisfied.

To better quantify this phenomenon, let us consider a hypothetical network consisting of a set of clients $\mathcal{X}$. Let X_i be the set of clients forwarding on exactly i interfaces; then $\mathcal{X} = \bigcup_{i \geq 1} X_i$. We will refer to unicasting clients as $\mathcal{U} = X_1$, and multicasting clients as $\mathcal{M} = \bigcup_{i>1} X_i$. Assume that any multicasting client employs *UNM* as its forwarding strategy. For convenience, we define the fraction of clients employing multicast as $\alpha = |\mathcal{M}|/|\mathcal{X}|$.

If each client generates requests at a rate of r packets per second, then the total number of fundamentally unique interests generated over a period of T seconds is given by $rT|\mathcal{X}|$. Ideally, this should also provide an upper bound on the total number of content objects delivered to clients across the network. However, the amount of data delivered by the network in case of *UNM* is given by the following equation:

$$rT\Big(\sum_{i \geq 1} i|X_i|\Big). \tag{3.1}$$

In Fig. 2, we show the result of our numerical calculations regarding the number of content objects delivered to clients in networks containing $X \in \{40, 80, 120\}$ clients and with $\alpha \in \{1, 0.75, 0.5, 0.25\}$. For purpose of visualization, we have chosen to analyze the case of $r = 10$ interests per second with $T = 300$ seconds of activity, where all multicasting clients have three interfaces ($\mathcal{M} = X_3$). Note that the number of data packets delivered increases as the fraction of multicasting clients (α) increases; when $\alpha = 1$, the result matches the optimum value of $rT|\mathcal{X}|$.

This behavior of *UNM* actually represents a worst-case scenario in terms of redundant data delivery in a situation where a non-empty subset of clients employ multicast forwarding. In the ideal case, the total number of deliveries will always be $rT|\mathcal{X}|$, as each request results in exactly one content delivery. When employing standard multicast strategies such as those mentioned in Section 1, the number of content packets delivered will be bounded below by $rT|\mathcal{X}|$ and above by Equation 3.1.

Though redundant content delivery indeed burdens the network, *UNM* also has a much more serious problem: it offloads the responsibility of mitigating *iDoS* onto clients. In addition to the impossibility of ensuring that all legitimate multicasting clients use *UNM*, there is no way to prevent a malicious client from choosing not to install it. Therefore, in the next section we propose an alternate mitigation to *iDoS* which does not depend on the behavior of clients, and instead employs an in-network reactive approach.

Algorithm 1 Algorithm for *RRT*.

Input: Duplicate-nonce NACK N_k received on face f for interest k with nonce n.

```
1:  if numNoncesInPITEntry(k) > 1 then
2:      K = getInterestsInPITEntry(k)
3:      for each interest k' ∈ K do
4:          if getNonce(k') ≠ n then
5:              sendInterest(k', f)
6:              break
7:          end if
8:      end for
9:  end if
10: r = getInFace(k)
11: sendNACK(N_k, r)
```

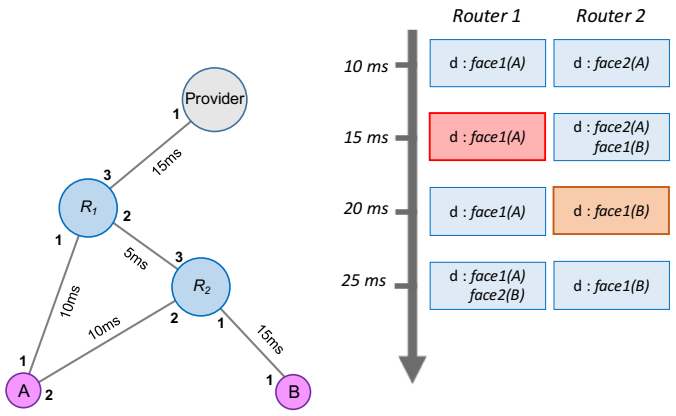
4. In-Network Approach

In this section, we discuss a mitigation to *iDoS* which employs in-network retransmissions of NACKed interests to ensure content delivery. Different from [12] where in-network retransmissions are utilized to avoid loop-detection NACKs to allow face probing, we use in-network retransmission to ensure delivery to all clients in the network.

A. Solution Description

To mitigate *iDoS* without relying on the cooperation of all clients, we propose a modified forwarding strategy meant to be deployed in the core of the network. This strategy is henceforth referred to as Request Re-Transmit (*RRT*). Under *RRT*, routers may retransmit interests which are NACKed due to duplicate nonces, and thereby ensure that all consumers receive the content objects they have requested.

Algorithm 1 details the procedure followed by an in-network router implementing *RRT*, upon the receipt of a duplicate-nonce NACK for interest k. On receiving the NACK, the router checks the PIT entry associated with the NACKed interest to determine whether any additional interests $k' \in K$ were aggregated with it (Line 1). If such an interest exists, it will have a different nonce associated with it. Therefore, the router can retransmit that aggregated interest back on the face on which it received the NACK (Lines 2-8). Finally, the router forwards the NACK



(a) Network topology (b) Routers' PITs in time

Fig. 3: Working example of *RRT*.

downstream on the face from which it originally received the NACKed interest (Lines 10-11).

Fig. 3 illustrates a working example of this technique. As in the earlier example, both clients A and B request d simultaneously, and A multicasts its interests. In this example, both Router 1 (R_1) and Router 2 (R_2) are using *RRT*. For clarity, we again use the client names (A and B) to represent the nonces for their interests. As shown in Fig. 3(b), at time step 10 ms, R_1 receives a request for d from its *face1* and R_2 receives the same request over its *face2*. At time step 15 ms, R_2 receives a new request for d over *face1*, and hence aggregates it with the entry it has in its PIT. At the same time, R_1 receives the same request (identical nonce) it received at time 10 ms from its *face2*. Since the request has the same content name and *nonce* value, R_1 detects it as a duplicate request (red shaded entry in Fig. 3(b)). Due to the request being a duplicate, R_1 did not add *face2* to its existing PIT entry for the request for content d, but instead sent a NACK down on *face2* towards R_2.

At 20 ms, R_2 receives the duplicate NACK and detects that it has an aggregated interest for *face1*. R_2 retransmits the interest with the nonce associated with *face1* up to R_1. It also removes *face2* from its PIT and forwards the NACK down on *face2* (orange shaded entry). When R_1 receives data at time step 40 ms, it would forward it on both *face1* and *face2*. R_2 forwards data only on *face1*. In this scenario, consumer A receives content d at time 50 ms via *face1*, and consumer B receives data at time 60 ms via *face1*. As illustrated in this example, *RRT* ensures that no client suffers packet loss due to *iDoS*.

B. Simulation Results and Analysis

Now, we present the performance analysis of *RRT* based on ndnSIM [13] (a module of ns-3).

We evaluated *RRT* on scale free networks generated according to the parameters in Table I. A given number of core routers were created, and some subset of them were then reassigned to be edge routers. A content provider was then attached to one of the edge routers; then, clients were attached to the edge routers deemed distant enough from the producer. In the 200-node network, the distance threshold was four hops; in the 400- and 600-node networks, the threshold was five hops. Unicast clients were each randomly given a single link to an edge router, and multicast clients were each given three random links to edge routers (while ensuring that no client is connected to the same edge router more than once). All client-to-edge-router links had 1 $Mbps$ bandwidth with 10 ms propagation delay, and the core of the network had links with 10 $Mbps$ bandwidth with 1 ms delay. We implemented *RRT* by modifying the BestRoute2 forwarding strategy available in ndnSIM according to Algorithm 1. We compared the performance of BestRoute2 (BEST) with that of *RRT* when deployed in the network core. All clients requested the same sequence of content objects from the producer at a rate of ten interests per second. The interest lifetime for the clients was set at 100 ms. We ran our simulations for 300 seconds and averaged the results for each topology over ten runs with distinct seeds.

TABLE I: Network Topologies with the Corresponding Number of entities

	Topo. 1	Topo. 2	Topo. 3
Core Routers	200	400	600
Edge Routers	30	60	120
Providers	1	1	1
Unicasting Clients	20	40	60
Multicasting Clients	20	40	60

We will evaluate the performance of *RRT* compared to BEST considering the following criteria: (i) Success rate (the ratio between the number of data packets received by the client and the number of interests), and (ii) Overhead (total number of excess interest and NACK packets seen in the network).

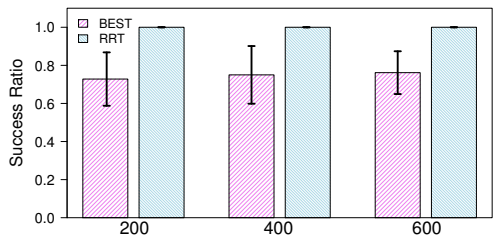
Fig. 4(a) shows the success rate of *RRT* compared to BEST. The wide variation in the success rate for BEST, reflected by its error bars, shows the non-deterministic nature of *iDoS*and its dependence on the network topology. However, *RRT* ensures that no requests are lost due to duplicate nonces; thus, 100% of requests are satisfied.

Fig. 4(b) shows the number of interests observed in the network. In each of the topologies, *RRT* shows higher interest overhead when compared to BEST, due to retransmissions.

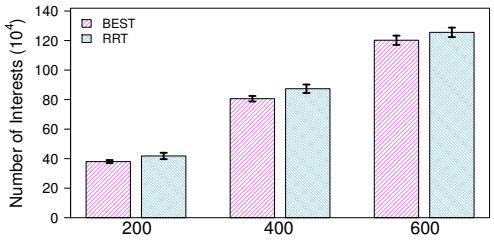
Fig. 4(c) shows the number of NACKs observed in the network. This figure shows that *RRT* results in fewer NACKs being propagated within the networks. In case of BEST, the clients which time out due to NACK retry the interests and compete for same data again which might cause more *iDoS* scenarios in the network resulting in more NACKs seen in the network.

Fig. 4(d) shows the total number of content objects delivered to clients, including redundant deliveries. As discussed in Sec. 3.2, redundant delivery is nearly inevitable when clients employ a multicasting strategy. Under BEST, a NACK results in an aggregated interest's entire delivery tree being pruned; however, *RRT* intentionally avoids this pruning step in order to increase content delivery success. Thus, in addition to increased satisfaction of interests which would have been lost under BEST, we also observe an increased rate of redundant delivery.

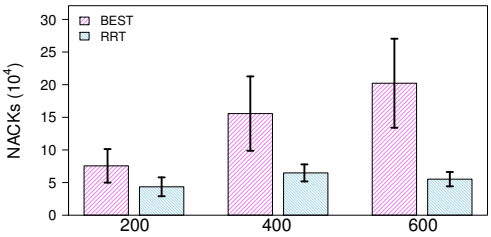
In addition to these analyses, we also measured content



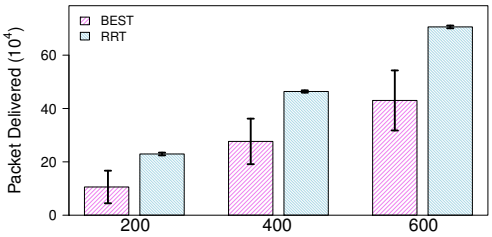
(a) Content delivery success rates.



(b) Number of interests observed in the network.



(c) Number of NACKs observed in the network.



(d) Total number of content objects (including redundancies) delivered.

Fig. 4: Comparison of success rates and overheads between *RRT* and BEST.

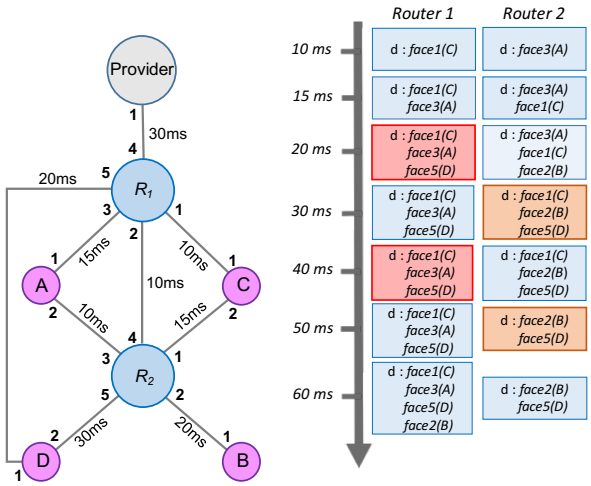
delivery latency in BEST and *RRT*. However, we observed that delivery latency under *RRT* follows the the same distribution as delivery latency under BEST. This result is attributable to the fact that in the topologies we studied, the total latency of the NACK generation and interest retransmission process is less than the content retrieval latency from the NACKing node to the content provider. Therefore, the PIT state in the upstream router will be corrected prior to it receiving the content object, and no additional delay is induced by the retransmission process. We also measured the number of retries required in the cases where *RRT* received a NACK, and determined that 96% to 98% of retransmitted interests are only retransmitted once. The remaining 2%-4% of cases where more than one retry occurs arise in cases where more than two requests are aggregated by the same router and more than one of the corresponding nonces is NACKed.

The results discussed above show that *RRT* is able to successfully and transparently mitigate *iDoS*, as it has satisfied 100% of requests in the evaluated scenarios without impacting client-observed latency. Though *RRT* reduces NACK overhead in the network, it does induce additional interest transmissions compared to BEST, and more importantly, exhibits a higher rate of redundant content delivery. Our goal with *RRT* was not to optimize for network overhead, but rather to ensure that user QoE is not impacted by *iDoS*. However, in the following section we we discuss potential directions for improvements to *RRT* which would reduce this overhead.

5. Discussion

The proposed *RRT* forwarding strategy leaves room for improvement in terms of interest and redundant content delivery overheads. As mentioned, a small portion of requests must be retried multiple times, due to the existence of multiple levels of aggregation in the network and multiple multicasting clients. If these additional retries are prevented, some network load can be reduced, and potential boundary cases where delivery latency is increased can be eliminated. Also, some amounts of redundant content delivery occurs naturally when clients multicast their requests. This overhead has a larger impact on the network. In this section, we provide a brief discussion of improvements to *RRT* that would mitigate both of these sources of overhead.

Fig. 5 illustrates an example of multiple retries and content deliveries. Clients A, B, C, and D request the same content d at the same time, with A, C, and D multicasting their interests. Both routers Router 1 (R_1) and Router 2 (R_2) are using *RRT*. We illustrate the PIT of each router in Fig. 5(b) with the *face* it receives the interest message on and the nonce of the interest generated by the client. For clarity, we use the client names, A, B, C, and D to represent the respective nonces in their interests. In Fig. 5(b), at time step 10 ms, R_1 receives a new



(a) Network topology

(b) Routers' PITs in time

Fig. 5: Illustration of retry and content redundancies.

request for d over its *face1* from C and R_2 receives the new request over its *face3* from A. Both R_1 and R_2 create PIT entries and forward the data towards the producer (*face4* for R_1 and *face4* for R_2).

At time step $15\ ms$, R_1 receives a new request over *face3* from A and hence aggregates it with the entry it has in its PIT. At the same time, R_2 receives a new request over *face1* from C and aggregates it into its PIT. At time step $20\ ms$, R_1 receives a new request over *face5* from D and aggregates it into its PIT. R_1 also receives a duplicate request (duplicate nonce) on *face2* for a content which matches the nonce A received on *face3*. R_1 does not aggregate this interest and sends a duplicate NACK down on *face2* (shown in red shaded entry). At the same time step, R_2 receives a new request over *face2* from B and aggregates it into its PIT.

At time step $30\ ms$, R_2 receives the NACK on *face4* matching nonce A for its entry for *face2*. R_2 removes the PIT entry for *face3* and sends NACK down on *face3* (shown in orange shaded region). R_2 also retransmits interest with nonce C up *face4* as part of the NACK handling operation of ***RRT***. R_2 also receives a new request over *face5* from D and aggregates it into its PIT. At time step $40\ ms$, R_1 receives a duplicate request on *face2* for content which matches nonce C (*face1*). R_1 does not aggregate this interest and sends a duplicate NACK down on *face2* (shown in red shaded entry).

At time step $50\ ms$, R_2 receives the NACK on *face4* matching nonce C for its entry for *face1*, R_2 removes the PIT entry for *face1* and sends NACK down on *face1* (shown in orange shaded region). R_2 also retransmits interest with nonce B up *face4* as part of the NACK handling operation of ***RRT***. At time step $60\ ms$, R_1 receives a new request over *face2* with nonce B and hence aggregates it with the entry it has in its PIT. At time step $70\ ms$, R_1 would receive data from *face4* and forward it down on *face1*, *face2* and *face3*. At time step $80\ ms$, R_2 would receive data from *face4* and forward it down on *face2*. In the given example all clients received data (Client A at $85\ ms$, Client B at $100\ ms$, Client C at $80\ ms$, and Client D at $90\ ms$ and $110\ ms$), and R_2 had to retransmit interests two times on *face4* (at time step $30\ ms$ and $50\ ms$).

This example shows that in a large network these kind of retries and redundant content deliveries (e.g., to D) could end up being significant. To reduce these redundancies, there needs to be a modification at the router (R_i) which initiates the NACK due to receipt of duplicate interests. For example, a potential modification is for R_1 to include all the nonces in the aggregated PIT entry in the NACK for a duplicate interest. This would give more information to downstream routers (closer to clients) when they receive the NACK. For example, at time $20\ ms$, R_1 could add its set of nonces $\{A, C, D\}$, with the NACK. That would prevent R_2 from sending the interest for C again at time $25\ ms$ and retry with interests for B. In turn, R_2 can NACK back to A, C, and D. This prevents redundant data delivery to D.

If the downstream routers have interests aggregated with nonces different from the list of nonces included in the NACK, they can choose to retransmit the interest which will get aggregated at R_i without multiple retries. If the nonces of aggregated interests from downstream routers are included in the NACK, then downstream routers will not redundantly retransmit interests up towards the producer. This solution will decrease the number of in-network interest retransmissions and redundant data deliveries resulting in reduced network overhead.

This solution requires modification to the structure of NACKs as well as the forwarding behavior of nodes. Due to lack of time, we have not implemented this solution in ndnSIM; the modifications require changes in many facets of the NFD.

6. Conclusions

In this paper, we demonstrated the scenario where multicasting clients in NDN networks can end up staging an implicit DoS attack on other clients. We discussed three solutions, ***UNM***, ***RRT***, and an improvement to ***RRT***, to mitigate the implicit DoS scenario. We implemented ***RRT*** and showed that it can successfully prevent the implicit DoS of clients. We did not implement the improved version of ***RRT*** discussed in Section 5 as it needs modification to the core ndnSIM structure and NACK packets, which we will explore in the near future.

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