# Content Discovery in Opportunistic Content-Centric Networks

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***Abstract*— Host-based mobile ad hoc communication requires the transmission of periodic hello beacons to identify neighbors. Drawing conclusions from received beacons, e.g., containing information about existence and neighbor nodes, to available or demanded content is not possible and the gathered information may be outdated quickly due to dynamic environment changes. Therefore, content-centric networking results in more flexible communication without the need of neighbor information. Instead, information about available content is required. In this paper, we will investigate two different content discovery strategies and discuss their efficiency for mobile communication. The algorithms have been implemented in the CCNx framework and evaluated in VirtualMesh, a hybrid emulation tool for wireless mobile ad hoc networks.**

***Index Terms*—discovery, content-centric, opportunistic, ad-hoc networks**

## I. Introduction

Content-centric networks are a new networking paradigm for the future Internet. Routing is performed based on content identifiers instead of IP addresses. The approach addresses scalability, security and efficiency concerns of the current host-based Internet architecture. Many different architectures have been proposed, [1], [2], [3], [4], which mainly differ in the way content is named. Hosts need to express interests in, or subscribe to, names to get the corresponding objects published by a content source. In this paper, we focus on the Content-Centric Networking approach proposed in [4], which is hereafter referred as CCN. Although current research mainly targets wired networks, CCN has already been identified [5] as promising approach for mobile and dynamic networks since communication is more resilient to individual node mobility. Instead of trying to reach a specific host, the user tries to get a specific piece of content that can be provided from any other node that holds the content. Most current research works target caching, security and forwarding strategies in CCN. In this work, we investigate a more fundamental requirement, namely, the discovery of available content in a distributed wireless broadcast environment. This is required in scenarios without centralized directories where content objects are generated dynamically and names cannot be predicted deterministically. It enables users to learn available content objects and services without demanding the entire content. Instead of connecting individually to each host, the requester can express an Interest and receive an answer from any reachable content source given that the content is available.

The remainder of this paper is organized as follows: In section II we shortly review the basic functionality of CCN. Related work to CCN is reviewed in section III. Section IV describes content discovery algorithms. Evaluation results are presented and discussed in section V. Finally, in section VI, we conclude our work and give prospects to future work.

## II. Content-Centric Networking

In this section, we will briefly describe the main concept of CCN. Readers may refer to [4] for more information.

### A. CCN Messages

CCN communication is based on two basic messages: *Interest* and *Data*. Content is organized in segments similar to chunks in BitTorrent [6]. File transfer is pull-based, and thus, users have to express Interests in every segment to obtain the entire content. The CCNx project [7] provides an open source reference implementation of CCN.

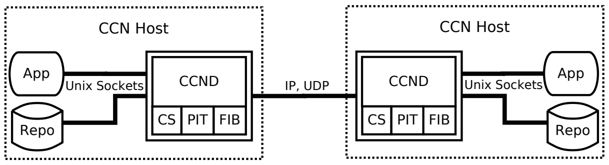


Fig. 1: Forwarding Architecture

The core element of the implementation is the CCN daemon (CCND), which performs the message processing and forwarding decisions. The connections from a CCND to other entities or local applications are called *faces*. In case of applications, the face corresponds to local Unix sockets. In case of mobile hosts, it corresponds to UDP or TCP sockets over IP. In this work, we use a multicast face using UDP and a multicast address to avoid individual IP addressing of mobile nodes.

Figure 1 shows the processing and forwarding architecture of CCNx. If an application on a node requests content, it sends an Interest message via a local face to the CCND on the local host. The CCND processes the message based on its information in the content store (CS), the pending Interest table (PIT) and the forwarding Interest base (FIB). Upon the reception of the Interest, the CCND will first check if the content is already in the CS, i.e. serving as a cache, and returns it if available and not expired. If the content is not available, it will check the PIT whether the same request has already been expressed. The lifetime of an Interest will determine how long it stays in the PIT. If it is already in the PIT, the Interest can be discarded, because the corresponding data message is already pending. If there is no entry in the PIT, the host considers the FIB to check whether the host knows where to get the content from. If there is an entry, the Interest is inserted into the PIT and forwarded to a remote CCND, e.g., via the wireless channel using UDP as transport protocol. At the remote CCND, the procedure of checking the CS, PIT and FIB will be repeated. Content is persistently stored and shared with others in content repositories. CCN hosts that run a content repository can register the available prefix to their local CCND resulting in an additional FIB entry. Every Interest will result in at most one Data message and retransmission of the same Interest will result in the same Data message. To receive new content, it is required to either adapt the Interest prefix or add already received objects in the exclude field of the Interest.

### B. Content Names

In CCN, content names follow a hierarchical structure as illustrated in Figure 2. The ellipses correspond to name components and the rectangles to data files. Each data file consists of one or several segments (not depicted in the figure). There are no restrictions on content names and they can be selected arbitrarily. The hierarchical name structure may not indicate the location of content objects as Figure 2 shows. Content objects may be stored on one, multiple or all hosts. In contrast to flat name spaces, it is not required to agree on common keywords. These keywords should be diverse enough to describe all possible objects but not too diverse to avoid confusions with similar keywords. The hierarchical structure supports the discovery with general prefixes such as IDs from specific publishers. A user may look for specific content names relative to the publisher's name space, e.g., '/publisherA/video/' or '/publisherA/audio/'. Content consumers may learn the naming schemes of their favorite publishers such as BBC, iTunes or netflix. This also enables the integration of social structures to identify reliable content publishers.

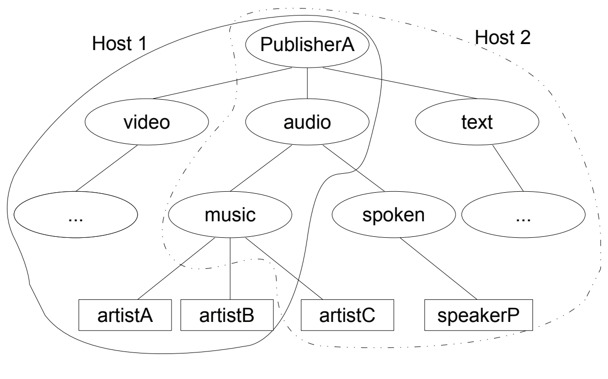


Fig. 2: Hierarchical Name Structure: files may be stored on different hosts.

## III. Related Work

Previous work in [8] investigated the applicability of existing MANET routing protocols for mobile CCN based on analytical models. Routing in CCN is equivalent to finding a content source for a given name. The authors conclude that structured solutions such as geographic hash tables should only be used in networks without host churn whereas unstructured flooding is beneficial in small networks with high host churn. In CCN, Interests are routed towards content based on content-specific routing table (FIB) entries whereas content objects travel the same path back from where the Interest arrived. In a broadcast domain, this would result in unbounded Interest forwarding until the entire network is covered. CCN does not consider any multihop suppression mechanisms to avoid unnecessary transmissions or collisions.

In [9], CCN is applied to artificial battlefield scenarios featuring group mobility and hierarchical network topology. Content publishers distribute meta data of generated content to their neighbors and domain gateways. This distributed information is then used by requesting nodes to forward Interests to content publishers. Additionally, a content pushing approach is proposed to distribute information from a command center via a backbone network to specific locations using geographical routing. In a simple testbed, the benefits of CCN over existing routing mechanisms such as the Optimized Link State Routing protocol (OLSR) are shown, but CCN relies on the hierarchical structure and meta data distribution for forwarding.

Resilience to individual node mobility independent of the network topology can only be achieved by broadcast communication, since no individual nodes need to be configured and any node may answer requests. Although introducing flexibility, unbounded broadcast transmission may quickly result in broadcast storms [10]. In [5] and [11], the authors introduce the Listen First, Broadcast Later (LFBL) algorithm, which limits forwarding of Interest messages at every node based on its relative distance to the content source. Additional header fields in the messages indicate the hop distance from the previous forwarder to the destination. These fields are modified at every hop and messages are only forwarded by nodes closer to the destination than the previous forwarder. Although the approach targets the suppression of unnecessary messages, it may not reach that goal reliably. Not protected by the author's signature, the distance fields may yield imprecise information due to node mobility, particularly if messages are transmitted from caches or in case of multicast communication.

In this work, we want to investigate content discovery mechanisms in distributed environments that are independent of potential subsequent file downloads. Based on the discovery information, users may decide which content files to download. We limit the communication to single-hop connections similar to communiation in delay-tolerant opportunistic networks [12]. Therefore, we rely on the suppression mechanism in CCN, which cancels a scheduled transmission if received from the same face. Routing is replaced by the mobility of nodes, caching and reexpression of Interests. In contrast to peer-to-peer based communication, e.g., in delay-tolerant networks such as Haggle [13] or PodNet [14], where all hosts periodically transmit hello beacons to keep track of neighboring hosts, no beaconing is required with CCN. A host expresses an Interest in a content file and receives data if it is available. Maintaining the neighbor list drains the energy of mobile devices, because beacons are transmitted periodically and independently of any data communication. In these systems, hosts subsequently connect to neighboring nodes to ask for available content. In case of dense urban environments and mobility, many subsequent connections may be required to find the desired content. In CCN, the requester may broadcast the Interest and any host that receives it and holds the corresponding content may respond. This may result in a faster discovery time, which is a crucial criterion if contact times are short.

Once the available content collections are known, a rich set of approaches exist in literature to discover availability of objects from these collections. Existing works in mobile ad hoc networks (MANETs) or delay-tolerant networks (DTNs) apply Bloom Filters [14] or attenuated Bloom Filters [15] to increase the efficiency of content or service discovery. If the synchronization of collections is targeted, the CCNx repository synchronization mechanism may be applied. It is based on a set reconciliation algorithm [16] that calculates the hashes of collections in a structured way. Such mechanisms may therefore optimize our discovery mechanisms, if the preferred collections are known, but can not replace them.

## IV. Content Discovery Mechanisms

Content discovery mechanisms are required in distributed environements where content objects are generated dynamically and names cannot be predicted deterministically. In the absence of centralized directories and periodic beaconing, users need to learn available content names before selectively requesting specific objects. This information is required to avoid the download of all available content objects resulting in congestion on the wireless medium.

Therefore, we describe two discovery approaches based on *name enumeration requests* and *regular Interests* hereafter.

As motivated in section I, the algorithms target single-hop communications. We rely on the suppression of data transmissions in CCN, which cancels the transmission of scheduled content if received on the same face: for example, if another node has already responded to an Interest with the same content object. We assume that every node runs a repository with persistent storage extending its local temporary cache and that these repositories are not synchronized among each other. Although answers from secondary storage are slower than from primary storage, additional repositories may help if cached copies are not available anymore or too far away.

The discovery mechanisms described in this section are based on the same idea: the discovering node expresses an Interest with a general prefix and waits for responses. Based on the response, subsequent Interests may be expressed. If no answer is received within a timeout period, the content is assumed to be unavailable. Since Interests are broadcasted, nodes cannot rely on MAC layer acknowledgements from the destination as for unicast transmissions and the sender cannot detect any collisions. Therefore, reliability functionality to identify collisions and to differentiate them from unavailable content needs to be performed by the requester. We achieve this by a retransmission counter: if no answer to a discovery request is received within the specified time, the requester reexpresses the request until a configurable limit of transmission attempts has been reached. When reaching the limit without receiving an answer, the content is assumed to be unavailable. In order to reduce the collision probability in the first place, the content sources answer a discovery request after an additional random answering delay. To adapt to dynamic changing environments and discover newly available content, the algorithms may be repeated periodically or based on external events such as overheard traffic or on-demand. In contrast to periodic beaconing the users may discover new available content instead of new peers.

### A. *Enumeration Request Discovery*

The Enumeration Request Discovery (ERD) requires the expression of name enumeration requests which are addressed only to local and remote repositories. A name enumeration request for a certain prefix requests the enumeration of first-level names under the prefix that are locally available at the repository. The requests are based on regular Interests but include command markers to indicate the enumeration. Figure 3 shows a sample message exchange for the naming tree in Figure 2. For simplicity, we do not show the command markers that are included in the requesting prefix and the returned enumeration name. The initial enumeration request for the prefix */publisherA/* triggers an answer including the next level components on both hosts, i.e., video, audio or text. The discovering node will process the first message received from host 1 and then reexpress the same Interest excluding the repositoryID from host 1, which is included in the received enumeration name and based on the repository's public key, in the third step. An answer to this request will be served either by the local CCND that cached the previous answer from host 2 or by host 2 itself if the cached entry expired. We always ask for the latest list version of the repository and let cached name enumeration requests timeout quickly.

The discovery procedure is described by algorithm 1. To discover the entire available name space, the algorithm starts from the top of the name tree with the shortest possible prefix and sequentially moves down to the leaves by increasing the prefix with the discovered name components after every timeout. At every iteration and level, the requesting user receives a list of available name components from the repository. We assume that the mobile repositories are not synchronized among each other and the content collections are not known. Therefore, the requesting user has to address each repository separately excluding the IDs from previous repositories to avoid inconsistencies. If the requester does not receive an

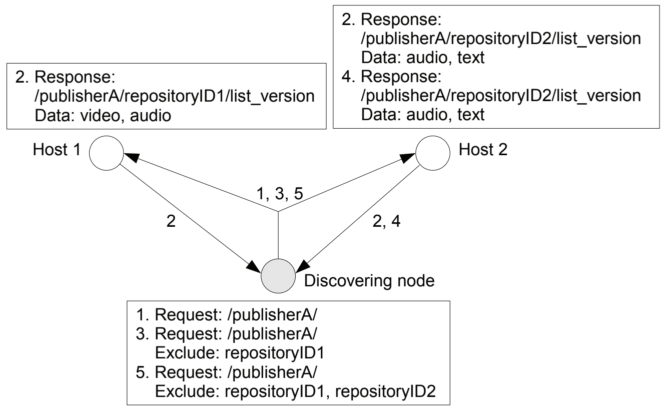


Fig. 3: Enumeration Request Discovery Sequence

**Algorithm 1** Enumeration Request Discovery

```
1:  $p$: requested starting prefix
2:  $L[r]$: prefix list of level $r$, initially $r = 0$
3:  $l_i$: component list of ith request
4:  $id_i$: id of ith repository
5:  function ENUMERATION($p$, $r$)
6:      $e$: exclude = {}
7:      $\{l_i, id_i\}$ = SEND_ENUMERATION ($p$, $e$)
8:      if timeout then
9:          return
10:     while no timeout do
11:         for all components $c_j$ in $l_i$ do
12:             $q$: prefix
13:             $p + c_j \to q$
14:             if $q \notin L[r]$ then
15:                 $q \to L[r]$
16:         $id_i \to e$
17:         i $\to i + 1$
18:         $\{l_i, id_i\}$ = SEND_ENUMERATION ($p$, $e$)
19:     for all $q$ in L[r] do
20:         ENUMERATION($q$, $r + 1$)
21:     return

22: function SEND_ENUMERATION($p$, $e$)
23:     broadcast enumeration Interest message with prefix $p$
24:     and exclude list $e$ containing all received $ids$
```

answer within a timeout period, it is assumed that no more content is available on any reachable host on that level. The algorithm procedes with the next component until receiving a timeout for all leaves of the tree.

## B. Regular Interest Discovery

The Regular Interest Discovery (RID) is based on the recursive expression of regular Interest messages. The user requests an Interest and receives the first data segment in the response. Although this leads to overhead because only the content name and no data is required, it is still more efficient than retrieving all data segments in complete file downloads.

A sample sequence for the name tree of Figure 2 is shown in Figure 4. The Interest expression in the prefix */publisherA/* will reach both hosts and trigger them to answer with the first segment of a matching content object. After the reception of the first segment of /publisherA/audio/music/artistA, the discovering node requests a new name component excluding the received artistA. Since host 2 has already sent this message in step 2, this request will not be forwarded to the wireless medium but answered from the local CCND's cache. Content segments must not expire as quickly as ERD content lists because they do not correspond to temporary repository listings but to existing content objects. Interests may therefore be satisfied from cache. We only discover the human readable part of the name, i.e., neglecting versions because these may be found by a version discovery once the name is known. The procedure is described by algorithm 2.

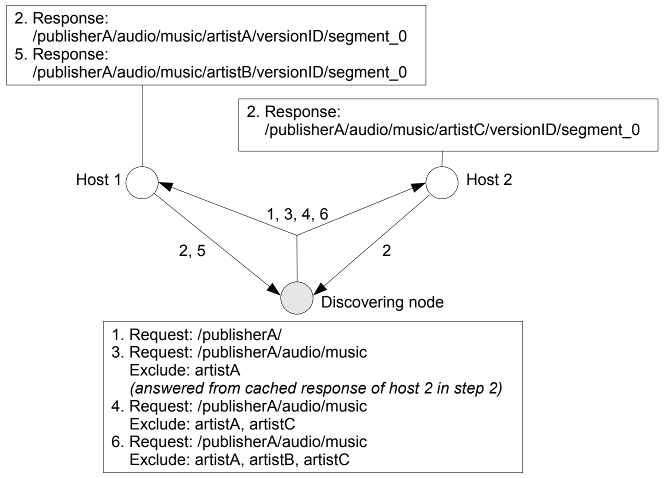

2. Response:
/publisherA/audio/music/artistA/versionID/segment_0
5. Response:
/publisherA/audio/music/artistB/versionID/segment_0
2. Response:
/publisherA/audio/music/artistC/versionID/segment_0
Host 1
Host 2
1, 3, 4, 6
2, 5
2
Discovering node
1. Request: /publisherA/
3. Request: /publisherA/audio/music
Exclude: artistA
(answered from cached response of host 2 in step 2)
4. Request: /publisherA/audio/music
Exclude: artistA, artistC
6. Request: /publisherA/audio/music
Exclude: artistA, artistB, artistC

Fig. 4: Regular Interest Discovery Sequence

**Algorithm 2** Regular Interest Discovery

```
1:  $p$: request prefix
2:  $L$: name list, initially $L = \{\}$
3:  $c$: received content name with $c[i]$, $i = 1, ..., n$ components
4:  $s$: prefix size

5:  function DISCOVERY($p$)
6:      e: exclude = {}
7:      s = size(p)
8:      c = SEND_INTEREST ($p$, $s$, $e$)
9:      if no timeout then
10:         RECURSIVE($c$, $s$)
11:     return

12: function RECURSIVE($c$, $s$)
13:     e: exclude = {}
14:     do {
15:     if size(c) > s+1 then
16:         RECURSIVE($c$, $s + 1$)
17:     else
18:         c $\to L$
19:         if size(c) == s then
20:             return
21:     c[s+1] $\to e$
22:     c = SEND_INTEREST ($c$, $s$, $e$)
23:     }
24:     while(no timeout)
25:
26:     return

27: function SEND_INTEREST($b$, $s$, $e$)
28:     broadcast Interest with first $s$ components of
29:     name $b$ and exclude list $e$
```

The algorithm starts by expressing a general prefix in a name space in the discovery function. After the reception of the first data segment, the mechanism knows the complete name of a content file at the leaf of the tree. By excluding the last components of the received objects, the algorithm searches only for new names. Because every transmitted packet contains only one content name, other nodes that overhear the traffic may cancel the transmission of redundant content objects. In case of a timeout, i.e., when the limit of the transmission counter has been reached, it is assumed that no additional content is available and the algorithm can move up one level by shortening the prefix by one name component and excluding this component in the Interest. The algorithm stops after a timeout at the initial discovery prefix, e.g., '/publisherA/' when all available next level components are excluded. Compared to the Enumeration Request Discovery, RID quickly finds available content objects at the leaves but requires the expression of new discovery requests for every component while ERD starts from the root and continously discovers multiple name components until receiving a content object.

## V. Evaluation

### A. Evaluation Tools

We implemented the Enumeration Request Discovery (ERD) and the Regular Interest Discovery (RID) algorithms described in section IV and integrated it with the CCNx source code v0.4.2. The implementations are evaluated by emulations with VirtualMesh [17]. VirtualMesh is a hybrid emulation tool that combines the real network stack and the CCNx implementation running on virtualized hosts with simulations of the wireless communication. The wireless communication is simulated by the OMNeT++ [18] network simulator using the INET framework with the default 802.11b MAC layer implementation. All CCNx messages are broadcasted using the default parameters and a static contention window of $32 \times 20\mu s = 640\mu s$. We do not consider any additional bit error models but only transmission errors due to collisions.

### B. Emulation Scenarios

The algorithms are evaluated in a static setting of 5 nodes. Due to single-hop single-radio communication, we assume that all nodes can directly communicate with each other. One node, the *discovering node*, performs the discovery operation and the other nodes are hosts running repositories containing different content files. We differentiate between two basic content distributions in our evaluations:

1) *Common case*: all repositories store exactly the same content objects and
2) *Distinct case*: every content object is uniquely stored at only one of the repositories.

All content objects are named under the same hierarchy level by '/prefix/<content #>'. The discovery algorithms are implemented as applications forwarding Interests via the local face to the CCND. If the content is in the CCND's cache, it will be returned immediately without forwarding the Interest to the wireless medium, otherwise it is forwarded to other nodes and temporarily included in the PIT, as explained in subsection II-A. All received content information remains valid in the cache for the entire duration of the discovery. Before every discovery evaluation is started, all CCND caches are cleared. Both discovery algorithms will express Interests in the general prefix '/prefix/' to discover the available content objects at all repositories. Based on the reception of a discovery response, the mechanism will express the next Interest excluding already received information as explained in section IV. The discovery responses differ for ERD and RID: in case of ERD, it is the ERD content list containing the available content names at the corresponding repository. In case of RID, it is the first segment of a content object. Therefore, ERD requires the expression of one Interest per repository node to receive all content lists while RID requires the expression of one Interest per available content object. We use the default segment size of 4096 Bytes. The Interest lifetime is set to 0.5 seconds and we perform a retransmission of the same Interest after a retransmission delay of 0.6 seconds if no response has been received. The retransmission delay is slightly larger than the Interest lifetime to ensure that the existing PIT entry has expired and the retransmitted Interest can be forwarded by the local CCND. If not stated otherwise, we use a retransmission limit of two retransmissions before a timeout is assumed. Since discovery mechanisms should not overload the medium with traffic, we evaluate different delay parameters influencing the number of retransmissions and the discovery time in subsection V-C. The discovery time is defined as time until the discovering node has discovered all content names and detected a timeout. Based on these findings, we evaluate both discovery mechanisms for different numbers of content objects and distributions in subsection V-D.

### C. Discovery Delays

Broadcast requests may trigger potentially many responders. Therefore, we will evaluate different delay parameters and their impact on retransmissions and duplicate content transmissions in this subsection. The evaluations apply to both ERD and RID but due to space limitations we only show the results for RID. The answering delay (AD) defines the interval [AD, 3AD] within which each host randomly selects a time to answer a request. Once scheduled, the content object stays in the senders' send queue until the answering delay is due; then it is forwarded to lower layers for transmission. A long AD may increase the individual discovery time but enables other hosts to detect concurrent responses.

Figure 5 shows the performance of RID discovery if the network comprises 40 different content objects, which are all stored on all hosts, i.e. the common case. The x-axis denotes the different answering delays in milliseconds. The figure shows the transmitted requests and received messages at the discovering node as well as the time to discover all content objects, i.e. the discovery time. As expected, the number of received content duplicates is higher with short answering delays and decreases significantly with higher values. At an AD of 10ms, the number of received duplicates is even higher

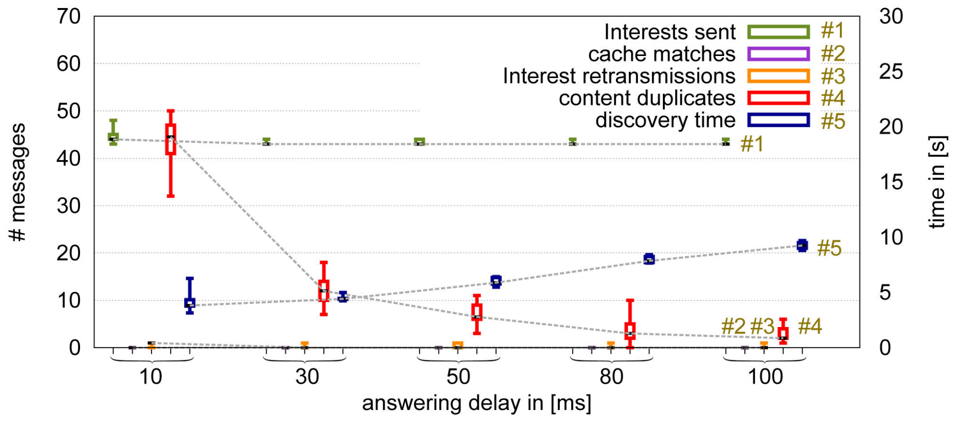


Fig. 5: RID discovery of 40 content objects in the common case

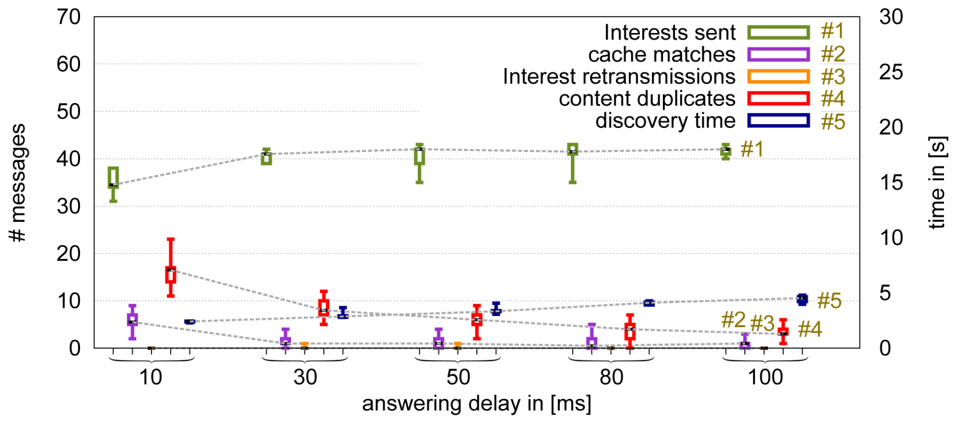
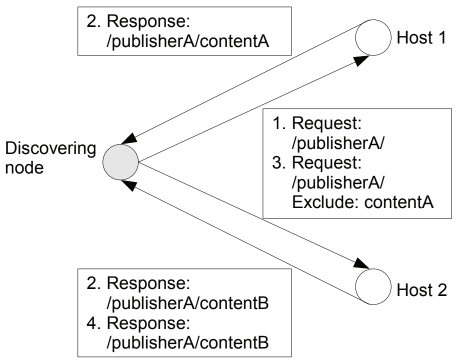


Fig. 6: RID discovery of 40 content objects in the distinct case

than the number of transmitted Interests. Because of the small AD value, the hosts schedule their content transmission almost at the same time not leaving enough time to detect and suppress concurrent transmissions. As soon as the messages are forwarded from the send queue to the lower layers, no cancelation is possible anymore. The number of required Interest retransmissions is suprisingly low: at an AD of 10ms, every Interest is retransmitted at most once. For the discovery of 40 content objects, such retransmissions occured at most five times when using an AD of 10ms and at most once when using an AD of 30ms or higher. Since all content objects are stored on all hosts, every Interest will trigger the same answer from all hosts. Given that the discovering node's cache is empty when starting the discovery operation, no Interest requests can be matched from the local CCND's cache. Therefore, to discover 40 objects, the discovering node transmits at least 43 Interests: 40 Interests to discover the objects and 3 additional Interests to detect a timeout using the retransmission limit of 2.

Figure 6 shows the results for the discovering node when using RID discovery of 40 content objects stored uniquely at different nodes, i.e. distinct case. Since every content object is only stored at one node, every request with the general */prefix/* will trigger different responses from the repositories. Since the transmitted content is not the same, the hosts do not cancel their scheduled content transmission in case of overheard transmissions because they cannot uniquely relate their content transmission to the same Interest. Therefore, the discovering node's CCND may receive multiple content objects per Interest but only one content object per Interest is forwarded to the discovering application. Subsequent Interests may then be matched from CCND's cache and may not be transmitted over the wireless medium anymore but the percentage of cache matches is quite low as Figure 6 shows. The discovery time for RID is approximately halved compared to the common case since different hosts may reply to the same Interest with different content objects resulting in a faster discovery.

Surprisingly, although all content objects are uniquely stored at only one host, content duplicates occur for all AD values in Figure 6. The reason for that is the fact that subsequent Interests are expressed immediately after the reception of a content object resulting in duplicates in case of unsynchronized repositories. We illustrate the problem with the help of Figure 7 where two hosts store different content objects. An Interest in the general prefix '/publisherA/' triggers different responses from both hosts. While host 1 answers



2. Response: /publisherA/contentA
Host 1
Discovering node
1. Request: /publisherA/
3. Request: /publisherA/ Exclude: contentA
Host 2
2. Response: /publisherA/contentB
4. Response: /publisherA/contentB

Fig. 7: Content duplicates due to unsynchronized repositories

with 'contentA', host 2 may schedule the transmission of 'contentB'. If the discovery node would express a subsequent Interest immediately after receiving 'contentA' from host 1 but before receiving 'contentB' from host2, it would address host 2 twice. If host 2 has already scheduled the content, i.e. removed from it's send queue and forwarded to lower layers, it cannot remember the previous transmission and sends a duplicate content. Therefore, we apply an additional Interest transmission delay (TD) at the discovering node. Whenever a discovery response is received, the discovering node delays the transmission of the subsequent Interest by TD. We set $TD = 2 \times AD$, i.e. the maximum time difference between two content transmissions. This enables the reception of answers from other nodes before the expression of the next subsequent Interest. If different content objects are received, the Interest may be satisfied from the local CCND's cache. Otherwise, it is forwarded to the wireless medium.

Figure 8 shows the differences in transmitted Interests and local cache matches when applying TD=2AD. It can be seen that if TD is applied, three times more Interest requests can be satisfied from the cache and, therefore, fewer Interests have to be transmitted over the wireless medium. In Figure 9 the differences regarding received content duplicates and discovery time are shown. For TD=2AD we can avoid the reception of any duplicates relieving the wireless medium from unnecessary transmissions. The discovery time increases only moderately for small AD values.

In the following evaluations, we set AD=50ms and TD=2AD. This avoids all duplicates in the distinct case and results in a low number of content duplicates in the common case. It is not possible to avoid duplicates in the common case completely because two senders may always select the

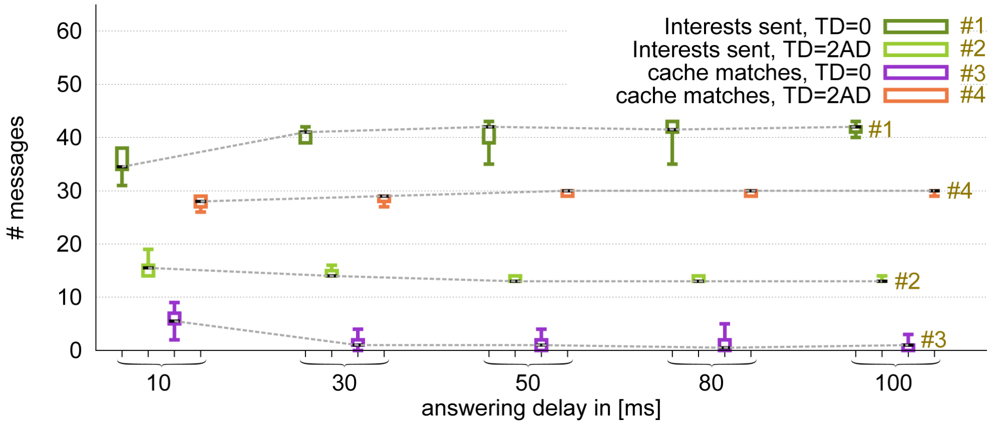


Fig. 8: RID discovery with TD=2AD vs. TD=0 in the distinct case

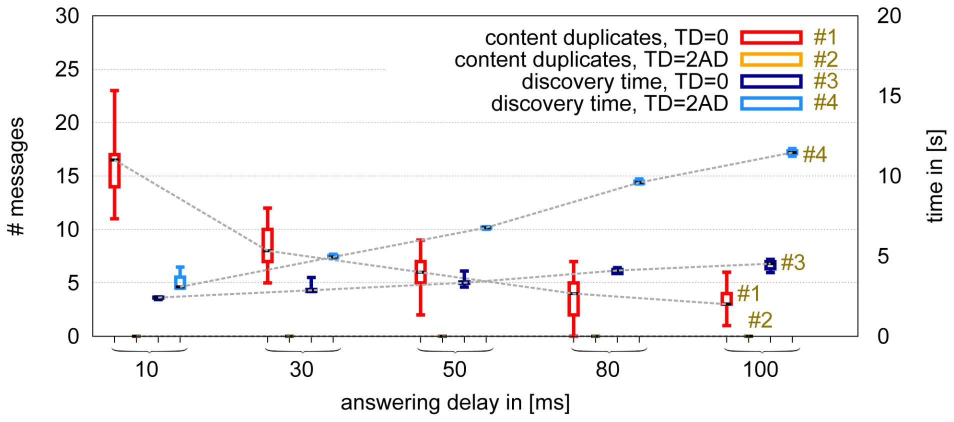


Fig. 9: RID discovery with TD=2AD vs. TD=0 in the distinct case

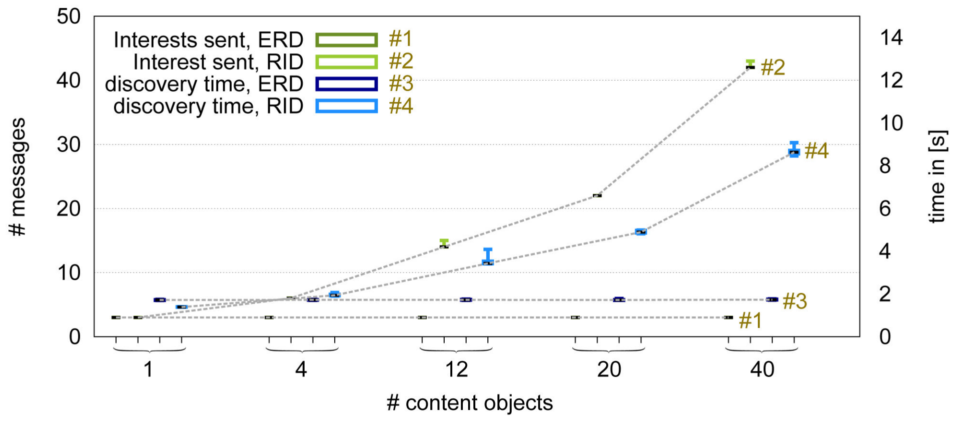


Fig. 10: Comparison between ERD vs. RID in the common case.

same answering time with a certain probability depending on the AD length. We observed in our evaluations that AD values above 50ms do not reduce the number of received duplicates significantly but result in a much larger discovery time. Since in all our evaluations, retransmissions occured very infrequently and at most once per Interest, we set the retransmission counter limit to 1. Although higher network congestion levels may require higher retransmission limits to discover content, it may result in even higher congestion aggravating the traffic situation. In highly congested networks, we can therefore consider the corresponding content objects as (temporarily) unavailable.

### D. *Enumeration Request vs. Regular Interest Discovery*

In this subsection, we compare Enumeration Request Discovery (ERD) and Regular Interest Discovery (RID) with respect to time and number of transmitted and received messages. We use an answering delay of AD=50ms and set TD=2AD. The retransmission counter limit is set to 1 retransmission resulting in 2 unresponded Interest transmissions before a timeout is detected.

The efficiency of ERD and RID is evaluated in the same 5-nodes scenario as described in subsection V-B. We consider different numbers of content objects and content distributions, i.e. common and distinct, in the network. All hosts either comprise 1, 4, 12, 20, or 40 content objects. Figure 10 shows the difference in number of transmitted Interests and discovery time if all hosts have the same content. The x-axis denotes different numbers of content objects. If only one content object is available, RID is more efficient, since it cannot learn anything new after the first request and the discovery stops quickly. On the contrary, ERD requests the ERD content list from all hosts. Only after checking all names on all lists, the discovering node can be certain to have received everything. This requires multiple discovery requests. However, due to the general ERD request prefixes, subsequent requests for content lists may be answered from the cache. The number of ERD requests does not depend on the number of content objects on hosts but the number of hosts in the vicinity. Therefore, the number of ERD requests and the discovery time is constant in our setting for all content configurations. On the contrary, the number of transmitted Interest messages and discovery responses increase significantly for RID with increasing number of content objects. If all hosts store the same content objects, the requester has to express an Interest for every single content object. Since RID requests ask for the first data segment, the transmission of the corresponding responses requires considerably more time.

The figure showing the results in the distinct case is omitted due to space limitations. If only one content object is stored in the distinct case at one node, only this node will respond to requests. Therefore, ERD performs similar to RID: only one request needs to be transmitted. However, RID performance degrades with increasing number of discovered content objects due to the increased number of discovery messages similar to the common case. As observed in subsection V-C, the same Interest request may trigger different answers from different hosts resulting in approximately 70% fewer transmitted Interests compared to the common case. This results in a slightly reduced discovery time because many packets may be satisfied from cache and only every fourth request needs to be transmitted.

The Enumeration Request Discovery (ERD) shows good performance in our evaluations, because it is independent of the number of content objects. However, the approach depends on the number of nodes in the network that store the requested content. Therefore, the approach may be inefficient in mobile scenarios with many nodes. Compared to RID, the ERD content lists of all repositories need to be processed and accumulated to know which content names are available. Therefore, if all hosts store the same content objects, ERD requires all nodes to request and process all content lists without learning something new. RID is more efficient to detect small differences in collections, because it can ask specifically for new content. Redundant information can already be excluded in the header to avoid duplicates. RID is also faster in finding a content object in a highly structured name space with many name components. In our evaluations, we considered a flat name space where ERD can perfom well. In a more structured name space ERD would require subsequent traversing through all name components until reaching the content objects. Therefore, the combination of both approaches may be promising. An initial RID request may quickly find the full name of a content object. By expressing an ERD request with the prefix of the received content object, a list containing other objects may be received from one repository. Instead of reexpressing other ERD requests, the requester may express RID requests excluding the learned information from the received ERD content list.

Discovery information from RID requests may stay for a longer time in the cache compared to ERD content lists since they correspond to existing content objects but not to temporary repository listings. Therefore, with RID discovery multiple nodes may collaborate and benefit from each others' discovery operations.

Both discovery mechanisms are not optimized yet and modifications are required to increase their efficiency. For example, ERD content lists may be identified by the hash of their content names instead of the repository identifiers to avoid multiple transmissions with the same information. On the other hand, Interests may be extended by a discovery flag, avoiding the transmission of the entire data object.

## VI. Conclusions and Future Work

Discovery of available names is very important in mobile CCN to learn what content is available. Users require this information to retrieve content in subsequent transmissions. We described two methods for content discovery: ERD is based on name enumeration requests and RID on regular Interests. The discovery algorithms target the wireless broadcast environment. Since wireless broadcast communication is unreliable and no MAC layer acknowledgments are available, discovery mechanisms have to account for occasional loss and collisions. Therefore, we included a retransmission counter that initiates a retransmission if no information is received within a timeout period. Evaluations showed that a retransmission limit of only one retransmission is enough to detect timeouts in our scenario. This can be interpreted as additional information being temporarily unavailable. In case of very congested networks, more collisions may occur resulting in higher counter limits but retransmitting discovery requests may even aggravate the situation. Avoiding collisions and received duplicates is another important factor for discovery. Evaluations showed that delaying the transmission of content objects helps reducing collisions and duplicate transmissions but this is not enough. In case of unsynchronized repositories, delaying the subsequent expression of discovery Interests may reduce the number of transmitted Interests and avoid received duplicates. ERD shows constant discovery performance in static settings independent of the number of contents in the network while RID decreases with the number of content objects. On the downside, ERD transmits a request to every node in the network and will therefore perform worse in mobile dynamic networks with many nodes or multiple nodes that have only a few common content objects. Since ERD responses carry the discovery information in the data, it is not possible to detect and suppress duplicate transmissions. RID holds the information in the name and hosts are therefore able to suppress duplicate transmissions. RID can efficiently and quickly find only a few content names in a dynamic network. As part of our future work, we target to extend our algorithms to multi-hop communication by developping adequate suppression mechanisms based on overheard traffic.

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