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Vassilakis, Vassilios, Wang, Liang, Carrea, Laura, Moscholios, Ioannis and Logothetis, Michael (2016) Scalable bloom-filter based content dissemination in community networks using information centric principles. In: IEICE Information and Communication Technology Forum (ICTF), 6-8 July 2016, Patras, Greece.

Scalable Bloom-Filter Based Content Dissemination in Community Networks using Information Centric Principles

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***Abstract*—Information-Centric Networking (ICN) is a new communication paradigm that shifts the focus from content location to content objects themselves. Users request the content by its name or some other form of identifier. Then, the network is responsible for locating the requested content and sending it to the users. Despite a large number of works on ICN in recent years, the problem of scalability of ICN systems has not been studied and addressed adequately. This is especially true when considering real-world deployments and the so-called *alternative networks* such as community networks. In this work, we explore the applicability of ICN principles in the challenging and unpredictable environments of community networks. In particular, we focus on stateless content dissemination based on Bloom filters (BFs). We highlight the scalability limitations of the classical single-stage BF based approach and argue that by enabling multiple BF stages would lead to performance enhancements. That is, a multi-stage BF based content dissemination mechanism could support large network topologies with heterogeneous traffic and diverse channel conditions. In addition to scalability improvements, this approach also is more secure with regard to Denial of Service attacks.**

I. Introduction

In traditional IP-based networks (e.g., the Internet) the communication between network entities is performed using location identifiers (i.e., the host IP address). It is argued that this, so-called Host-Centric Networking (HCN) paradigm is not well suited for today's communication needs [1]. Problems such as host mobility, content multicasting and multisourcing are hard to be efficiently addressed following the HCN principle. For example, talking about multisourcing, if the same content object is available from multiple locations (i.e., at hosts with different IP addresses) the network layer will not be able to exploit this fact to enable efficient content delivery. This problem of selecting the best content source will have to be addressed at a higher layer, thus causing lots of inefficiencies.

On the other hand, trying to address the aforementioned limitations, the Information-Centric Networking (ICN) [2] has emerged in the recent years. ICN shifts the focus from content location to content objects themselves. Users request the content by its name or some form of identifier and the network is responsible for locating the requested content and sending it to the users. To enable this functionality, network routers forward content objects based on content names, rather than the IP addresses.

Although ICN is an emerging technology, it already shows some promising results in the areas of content dissemination [3], [4], content consumer/provider mobility [5], [6], smart grids [7], [8], and security [9], [10]. There have been a number of ICN research projects, both in the United States and Europe, completed in the last years with remarkable achievements [11]. Also, some new ICN projects have recently started [12] - [14]. Among these ICN efforts, especially at their early stage, many adopted revolutionary approaches and envisioned replacing completely the current IP-based communication paradigm and infrastructure. On the other hand, some new ICN proposals adopt the evolutionary path that aims at co-existing with IP networks and improving their limitations [12], or at exploiting new opportunities brought by the ICN concept [13], [14]. Furthermore, the increasing popularity of the so-called *alternative networks* such as community networks [15], has led to research efforts that are trying to address their challenges using ICN principles. SCANDEX is one recently proposed ICN architecture for decentralised networks with challenged conditions [16].

A number of different forwarding mechanisms have been proposed for ICN. These mechanisms can be broadly classified into stateful [17], [18], stateless [19], and semi-stateless [20]. One example of ICN architecture that uses a stateful forwarding mechanism is the Named Data Networking (NDN) [21]. According to this approach, routers keep soft states for the pending content requests/interests. To avoid memory overflows, solutions based on hash tables and Bloom filters (BFs) [22], [23] have been proposed for NDN. On the other hand, the LIPSIN mechanism [19], currently used in the PURSUIT ICN [24], [25], encodes the delivery tree in the packet header in the form of a BF. This approach essentially eliminates the need for soft states at the routers. However, some scalability issues arise in terms of supported network size and the required packet header size [26].

In this work, we study the problem of integrating the ICN technology with existing non-ICN networks, identify the limitations of current ICN solutions and propose appropriate enhancements. In particular, we are concerned with the problem of strategically deploying ICN infrastructure to improve the performance of community networks from both operator's and user's perspective. To this end, and in order to enable cost-efficient solutions, we study the scalability of ICN content dissemination mechanisms in heterogeneous network environments, identify their limitations, and propose appropriate enhancements.

Scalability of stateful ICN forwarding mechanisms has been studied in a number of works [27], [28]. In this work, we focus on stateless ICN content dissemination. We first evaluate the LIPSIN mechanism, as one good representative for the stateless ICN approach, and reveal its scalability limitations in terms of supported network size. One of the factors that limits the scalability of this mechanism is its dependence on a single Bloom filter to encode the whole delivery path/tree. In the following, this is referred to as single-stage Bloom filter (SS-BF) approach. Next, we present an enhanced content dissemination mechanism that flexibly uses multi-stage Bloom filters (MS-BF) [29] to achieve good scalability. Hence, this approach can be seen as a generalisation of the basic LIPSIN mechanism.

This paper is structured as follows. In Section II, we review the related works on content dissemination and scalability in ICN. In Section III, we propose an ICN architecture for community networks and describe the network elements. In Section IV, we describe the main ICN functions and map them to the network elements. In Section V, we describe the realisation of BF-based content dissemination in our proposed network architecture. In particular, Subsection V-A describes the SS-BF based content delivery, whereas Subsection V-B describes the MS-BF based approach. We conclude and discuss our future work in Section VI. Also, in Table I we present the list of abbreviations used in the paper.

TABLE I
LIST OF ABBREVIATIONS

AS	Autonomous System
BF	Bloom Filter
BGF	Border Gateway Function
BN	Broker Node
CDF	Content Dissemination Function
CNO	Community Network Operator
CRF	Content Resolution Function
DoS	Denial-of-Service
E-GW	Edge Gateway
HCN	Host-Centric Networking
IC-FN	Information Centric Forwarding Node
ICN	Information Centric Networking
FIB	Forwarding Information Base
FId	Forwarding Identifier
FN	Forwarding Node
LId	Link Identifier
MS-BF	Multi-Stage Bloom Filter
NAF	Network Attachment Function
NDN	Named Data Networking
NCO	Non-Commercial Organisation
OFN	Operator Forwarding Node
QoE	Quality-of-Experience
RMF	Resource Management Function
SE-GW	Service Execution Gateway
SS-BF	Single-Stage Bloom Filter
UE	User Equipment
UFN	User Forwarding Node

II. Related Work

In this section, we briefly review some studies and solutions proposed to address the scalability challenges in ICN.

In [27], the basic principles for a scalable NDN forwarding plane are presented. The proposed design includes exact string matching with fast lookup and longest prefix matching for variable-length and unbounded content names. This can be achieved by simplifying the data structures and operational flows of the basic CCNx prototype [30]. However, an extensive scalability study is left for future work.

In [31], the architectural ICN scalability is studied from the viewpoint of content naming and user mobility. In this work, the NDN architectural framework is considered. The name resolution and mobility problems are efficiently addressed via keyword-based interest packets. Large-scale simulation experiments for real Internet topologies show good scalability of the proposed approach.

In [32], the scalability of the NDN Forwarding Information Base (FIB), which is used for content discovery, is studied. The proposed solution is based on assigning hierarchical content names by content providers and on naming aggregation. Some preliminary analytical studies indicate scalable data replication and good support for content mobility. Also, comparison with the CCNx prototype shows improved scalability in terms of the required FIB size.

In [33], a scalable name lookup operation based on tree bitmap and BF is proposed for NDN. The proposed solution enables efficient memory management, short lookup times, and imposes little overhead for updating operations even in large-scale scenarios. The experimental setup is based on analytical framework and includes a large number of name prefixes.

In [34], the problem of scalable and loop-free routing in NDN is studied. The proposed approach eliminates the need for per-packet in-network states, which are the main source for scalability limitations. This is achieved through a tag-based content address aggregation. The scalability evaluation in terms of storage and computational complexity is performed for realistic autonomous system (AS)-level topologies and for traces of popular applications.

In [35], a large-scale trace-driven analysis of ICN caching algorithms is performed. This study focuses on video-on-demand workloads and evaluates both network-centric and user-centric performance metrics for a wide range of content placement/replacement strategies and cache sizes.

A number of works tackle the scalability of ICN routing and forwarding functions by encoding the delivery path/tree in the packet header in the form of a BF. In [36], the LIPSIN mechanism of [19] has been extended using the MS-BF approach of [29]. The idea is to divide the content delivery path/tree into a number of stages and to encode the links of each stage into a separate BF. The benefit in terms of scalability comes from the possibility to individually optimize the size of the BF in each stage. An optimization framework targeting the elimination of false positives of the MS-BF forwarding mechanism is presented in [37]. Simulation and measurement results show reduced packet header sizes compared to LIPSIN as well as false-positive-free operation.

As discussed above, most of the existing ICN scalability studies either focus on very specific aspects, such as mobility, caching, and video delivery, or are based on small-scale evaluation scenarios. Also, most of the proposed solutions assume a relatively stable network infrastructure and do not take into account the peculiarities of networks with challenged conditions. On the contrary, our work targets a holistic evaluation and addresses the scalability problem of challenged and unpredictable environments of community networks.

III. Network Architecture and Components

In this section, we describe our proposed ICN-based architecture for community networks. The basic components of this architecture are (see also Fig. 1):

- *User Equipment* (UE): all sorts of commonly used user devices, such as laptops, smartphones, and desktop PCs. Users of a typical community network could be residential households, local businesses, and various non-commercial organisations (NCOs).
- *Forwarding Node* (FN): traditional networking equipment, such as IP routers and WiFi access points, to support communication between UEs. In a community network we typically have two types of FNs: a) User Forwarding Node (UFN): owned by users and, therefore, may be switched *on* and *off* or moved away from their current locations at arbitrary times. For example, when the user is not at home or the local business is closed during the night. b) Operator Forwarding Node (OFN): owned by the Community Network Operator (CNO), and, therefore, is expected to have more consistent and predictable operation. For example, OFNs are the equivalent of Super Nodes in the Guifi.Net [38] community network.
- *Information-Centric Forwarding Node* (IC-FN): FN enhanced with ICN features. It is typically owned by the CNO and is placed in strategic locations within the community network. Its role is: a) to respond to the dynamics of network connectivity, caused by instability of UNE, and b) to ensure acceptable Quality-of-Experience (QoE) of community users, by adapting the network resources to the dynamics of content demand. Specific functions of IC-NE are covered in Section IV, below.
- *Broker Node* (BN): special purpose ICN-enabled nodes that are owned by CNO and are responsible for content resolution and inter-domain content forwarding.

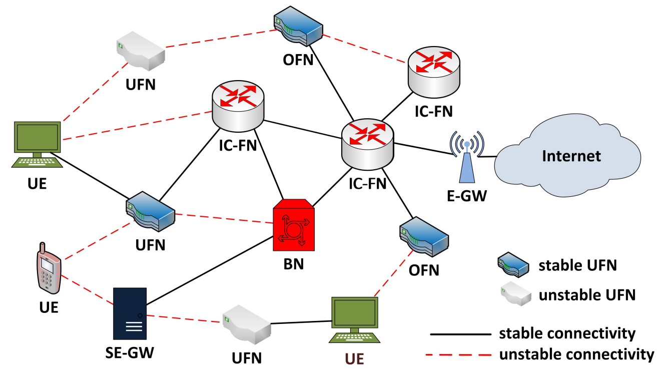

Fig. 1. Community network with ICN nodes.

- *Edge Gateway* (E-GW): owned by CNO and responsible for connecting to other domains and to external networks (e.g., the Internet).
- *Service Execution Gateway* (SE-GW): acts as the attachment point for non-ICN UEs that wish to access ICN services. A SE-GW is owned by the CNO and is responsible for translating non-ICN requests to ICN requests and vice versa.

In Fig. 1, some FNs are denoted as *stable* and some as *unstable*. Stable are typically OFNs as well as some UFNs which have been observed to have predictable behaviour (e.g., *on* during weekdays and *off* during weekends) and location. Unstable are some UFNs that have not been observed to follow any particular pattern. We also see that some links in Fig. 1 have stable connectivity (e.g., Ethernet or optical fibre) and some other are with unstable connectivity (e.g., WiFi). Stability of particular UEs and links, as we will see later, influences routing and caching decisions in the network.

UEs may act as *publishers* and *subscribers* for content items. Publishers (a.k.a. content sources) advertise the contents that they wish to share with other users. Subscribers (a.k.a. content requestors), on the contrary, are those who express their interest in receiving content.

IV. Information-Centric Functions

In this subsection, we present our proposed functions of IC-FNs and BNs and discuss their role in a community network.

A. Content Resolution Function (CRF)

The CRF is responsible for receiving the requests for a particular content from subscribers/requestors and for locating one or more content publishers/sources. It is also responsible for matching publishers and subscribers for a particular content item. The selection of appropriate content sources could be based on a number of factors, such as the distance or the current load [39]. We assume that the CRF is aware of the content location either via explicit notifications from content sources (i.e., according to ICN principles) or via traditional IP-based approach (i.e., acting as an IP gateway). CRF's role is similar, e.g., to the role of the Broker in SCANDEX [16] and of the Rendezvous Node in PURSUIT ICN [25].

B. *Resource Management Function (RMF)*

The RMF is responsible for the management of communication, computing, and storage resources. Also, it takes decisions for constructing the content delivery path/tree and for content caching [40]. In particular, it is responsible for efficient allocation of network resources to particular data flows when requested by the CRF. We assume that the RMF is aware of the network topology, links' characteristics, and devices' status.

RMF's role could be seen as an extension of the Topology Management Function of PURSUIT ICN, with additional storage and computing resources awareness. When the RMF receives a request from the CRF to construct a content delivery tree, e.g., from A to B and C, it does the following: a) Executes the MS-BF construction algorithm (described in Section V-B, below) to determine the best MS-BF stages for the content delivery tree according to any given constraints and optimisation objectives b) Encodes the delivery tree into the so-called Forwarding Identifier (FId) and sends it to the content source (if the source is ICN compatible) or to the SE-GW (if the source is not ICN compatible). Details of the FId encoding are given later in Section V-B.

C. *Content Dissemination Function (CDF)*

The CDF is responsible for disseminating the requested content to users. This is performed by forwarding the content to appropriate outgoing links, as specified by the FId (details later in Section V-B) That is, the CDF is responsible for forwarding the content to next-hop node. The forwarding decision is based on soft states [17], [4] or on in-packet information [19]. Furthermore, more advanced techniques, such as hash-routing can also be supported [41].

D. *Border Gateway Function (BGF)*

The BGF is responsible for connecting to non-ICN networks and, therefore, is located at E-GWs. The implementation of such function is outside the scope of this work. However, there have been research activities, which already show very promising results in this direction [12]. The idea is to use the IP addresses, which can be subscribed to using ICN primitives, and, as a consequence, would enable running IP flows over ICN infrastructure. Hence, and in order to avoid duplicating the existing research efforts, we assume that such a function is available.

E. *Network Attachment Function (NAF)*

The NAF is responsible for translating the non-ICN compatible requests (e.g., IP requests) into ICN requests and vice versa. Similarly to BGF, the design of NAF is outside the scope of this work and will be covered by the research activities of the POINT project [12].

V. Bloom Filter Based Content Dissemination

In this section, we describe the basic principles of traditional BF based content dissemination in ICN [19] and discuss its scalability limitations. We also describe a more enhanced approach, known as MS-BF based content dissemination [29]. In the following, the traditional BF is referred to as SS-BF.

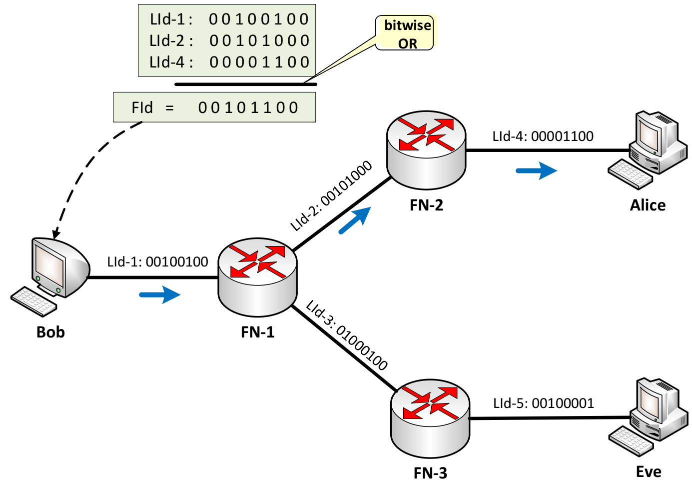

Fig. 2. Single-stage Bloom-filter based forwarding.

A. *Single-stage Bloom filter (SS-BF)*

An example of the SS-BF based packet forwarding is presented in Fig. 2. Consider three UEs (Bob, Alice, and Eve) and three FNs (FN-1, FN-2, and FN-3), connected as shown in Fig. 2. Each link has been assigned a unique m-bit Link Identifier (LId). For illustration purposes we use $m = 8$. Assume that Alice has subscribed to some content object that is available from Bob. Our aim is to encode the delivery path from Bob to Alice into a BF. This BF encoded path will be used to forward packets and is referred to as FId.

In the following, we describe: a) how to construct the FId and b) How to use the FId to forward packets. The construction of the Fid is performed by OR-ing the LIds of the links belonging to the delivery path. In this example, the desired path consists of LId-1, LId-2, and LId-4, and the FId is constructed as shown in the figure. FIds can be constructed either by the publisher itself or by some centralized entity (such as the BN) and sent to the publisher. When Bob obtains the FId, he will insert it in the packet header and will send the packet to its attached forwarding node, FN-1. FN-1 will perform the *forwarding test* on each of its outgoing links. The test is performed by AND-ing the FId with the LId of the link. If, and only if, the result is equal to the LId, the packet is forwarded via this link. As shown in the figure, the packet will be forwarded to FN-2, but not to FN-3, since the forwarding test for Lid-3 will fail. Consequently, FN-3 will perform the forwarding test on Lid-4 and, after having positive result, will forward the packet to Alice.

An important shortcoming of the BF based forwarding is the probability of *false positives* [42]. That is, there is some probability that the packet will be forwarded via a link that was not intended to be included during the FId creation. For example, assume that LId-3 =00110000. Since this link is not part of the delivery path from Bob to Alice, the constructed FId will be still the same as shown in Fig. 2. However, the forwarding test at FN-1 for LID-3 will give a (false-) positive result, and therefore a copy of the packet will also be forwarded to FN-3.

Note that, according to the FId construction method described above, the whole delivery path is encoded into a single BF. Hence, we refer to this approach as SS-BF.

B. Multi-stage Bloom filter (MS-BF)

Recent studies have shown that SS-BF based forwarding has some scalability limitations in terms of the number of supported links [26]. In particular, when the number of links is above 25-30, the probability of false positives becomes too high. This may severely degrade the network performance or even cause security problems [43], [44].

Therefore, we adopt the MS-BF based content dissemination approach. The idea is to divide the delivery path/tree into a number of stages. Links belonging to each stage will be encoded into an SS-BF, as described in Section V-A. Afterwards, multiple SS-BFs are combined into the MS-BF, which is used as the FId. This partition of the delivery path/tree into multiple stages provides greater flexibility in terms of optimising the BF length of each stage separately, while at the same time, enforcing an upper bound for false positives [37].

An example of the MS-BF-based packet forwarding is presented in Fig. 3. Bob, Carol, and Dave have requested a content object from Alice. We partition the delivery tree into two stages, with FN-4, FN-5, and FN-6 as the stage boundary nodes. Links of each stage are encoded into separate stage-BFs, as shown in the figure. Each stage may have different Lid length (and, hence, different BF length), m. The choice of the number of stages, stage boundaries, and stage-BF lengths, is subject to optimization and left as future work. In this example we use $m = 5$ and 4 for the first and the second stage, respectively.

After the construction of stage-BFs, the publisher (Alice) concatenates them and inserts into the packet header together with the information about the length of each stage-BF. The MS-BF packet forwarding process is similar to the SS-BF-based forwarding. Each FN performs the forwarding test for all outgoing links based on the corresponding stage-BF. In addition to that, the stage boundary FN also removes the BF of the previous stage. This way, the packet header shrinks as it traverses stage boundaries. When the packet finally reaches UEs, all BFs have been removed from the packet. This approach, apart from reducing the traffic overhead in the network, also hides from UEs the topology information. Hence, it will be harder for a malicious UE to employ reverse engineering techniques for launching Denial of Service (DoS) attacks [45], [46]. Another advantage of the MS-BF based approach is that the stage selection can be guided by a wide range of network- and user-centric metrics, such as topology characteristics, spatial and temporal traffic demand, user device types and energy status.

VI. Conclusions and Future Work

In this paper, we propose an ICN based architecture for community networks. Initially, we describe the basic network

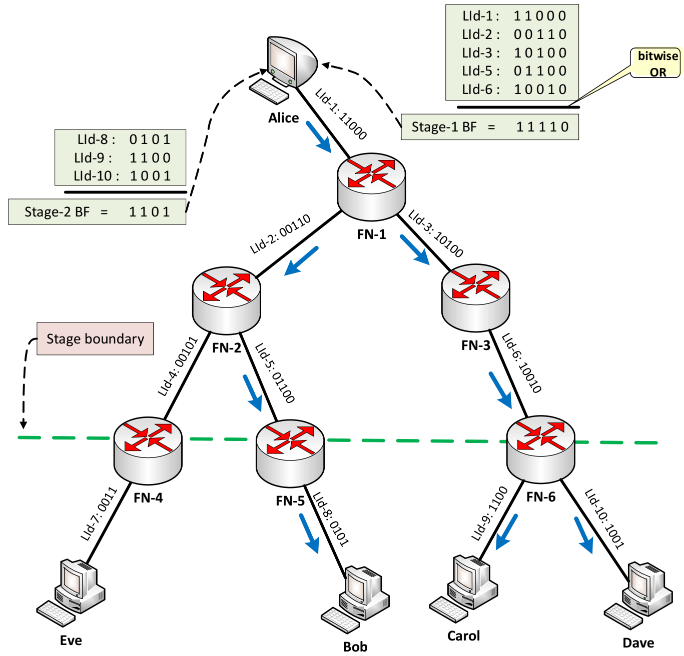

Fig. 3. Multi-stage Bloom filter based forwarding.

elements and functions. Next, we present two content dissemination techniques based on BFs. According to the SS-BF based technique, the whole delivery path/tree is encoded into a single BF. This approach has been shown to suffer from scalability and security problems. On the contrary, the MS-BF based technique divides the delivery path/tree into a number of stages and the links of each stage are encoded into different BFs. This approach has better scalability characteristics due to the possibility of independent BF length optimization within each stage. It also has better security features, since the topology information can be hidden from UEs if the corresponding BFs are removed from the packet header after each stage. This approach also enables dynamic BF reconfiguration in cases of failures or disruptions. In our future work we will study the problem of joint optimization of BF lengths in each stage.

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