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Efficient content delivery through fountain coding in opportunistic information-centric networks

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ABSTRACT

Opportunistic networks can increase network capacity, support collaborative downloading of content and offload traffic from a cellular to a cellular-assisted, device-to-device network. They can also support communication and content exchange when the cellular infrastructure is under severe stress and when the network is down or inaccessible. Fountain coding has been considered as especially suitable for lossy networks, providing reliable multicast transport without requiring feedback from receivers. It is also ideal for multi-path and multi-source communication that fits exceptionally well with opportunistic networks. In this paper, we propose a content-centric approach for disseminating content in opportunistic networks efficiently and reliably. Our approach is based on Information-Centric Networking (ICN) and employs fountain coding. When tied together, ICN and fountain coding provide a comprehensive solution that overcomes significant limitations of existing approaches. Extensive network simulations indicate that our approach is viable. Cache hit ratio can be increased by up to five times, while the overall network traffic load is reduced by up to four times compared to content dissemination on top of the standard Named Data Networking architecture.

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1. Introduction

Smartphones are nowadays ubiquitous. They support multiple wireless technologies, such as LTE, Wi-Fi, Wi-Fi Direct and Bluetooth, which allow them to flexibly access the Internet and communicate with devices in their vicinity. Modern smartphones are able to form wireless networks with other nearby devices opportunistically, while being connected to (and accessing the Internet through) Wi-Fi access points or cellular providers, e.g., [1,2]. The formation of such networks can also be assisted by cellular providers, e.g., [3,4]. The concept of opportunistic networking is about closing the gap between human and network behavior through the exploitation of the natural human mobility as an ideal opportunity to facilitate content dissemination [5–7]. Mobility, which is usually perceived as a degrading factor for the network performance, is now considered as an opportunity rather than a

challenge to cope with [8]. In an opportunistic network, devices spontaneously connect to each other (ideally without human intervention) and opportunistic network topologies change over time due to node mobility and energy preservation strategies (e.g., when a mobile device that is for instance a Wi-Fi Direct Group Owner passes ownership to become a regular client).

Opportunistic networks operate following the *store-carry-forward* paradigm, where intermediate nodes locally store and carry content until a forwarding opportunity arises. Usually, the terms opportunistic and delay-tolerant networks (DTNs) are used interchangeably, but according to the DTN definition given in [6] opportunistic networks correspond to a more general concept that includes DTNs. According to [6], DTNs consist of a network of independent networks that are presented with occasional communication opportunities among them with known and isolated disconnection points, whereas in opportunistic networks both disconnection points and communication opportunities are usually random.

Opportunistic networks can increase network capacity [9,10], support collaborative content downloading [11] and offload traffic from a cellular to a cellular-assisted device-to-device network

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[3,12]. They can also support communication and content exchange when the cellular infrastructure is under severe stress [2,13,14], since it is un-economical to provide more capacity (e.g., through portable cells or Wi-Fi access points) for events that take place rather infrequently. At the same time, opportunistic networks are the only means of communication when the network infrastructure is down or inaccessible due to natural disasters or government censorship (or just because it is not trusted¹). In most of the above-mentioned scenarios communication is all about the exchange of content (e.g., news, video-on-demand, emergency announcements, etc.), which in many cases can be of interest to multiple participants; e.g., updates on concurrent sports matches, departure times for public transportation after a football match, assembly points for emergency scenarios or public demonstrations, etc.

In opportunistic networks, connectivity among devices is intermittent and communication can be very lossy. This might decrease the possibility for successful content forwarding. However, the fact that user movement and mobility patterns have limited degree of freedom and variation, and rather exhibit structural patterns due to geographical and social constraints [8,15,16], minimizes this uncertainty. The dynamic and collaborative nature of opportunistic networks suggests that the usage of multiple content origins (along with caches) and multiple network paths to disseminate content would be extremely advantageous, especially when connectivity is not stable. The volatility of resource availability urges for efficient network utilization; e.g., avoiding unnecessary (re-)transmissions. At the same time, all these need to be supported in the context of a lossy wireless environment, calling for mechanisms that ensure reliable content delivery. All in all, caching, multi-source, multi-path and multicast forwarding, along with reliable content delivery emerge as crucial properties that opportunistic networks should support.

However, opportunistic networks are mainly built on top of TCP/IP, which only supports unicast data transport among devices (even if the underlying wireless medium is a broadcast one). Sporadic connectivity results in network layer configuration and requires TCP connection re-establishment as the network topology changes. Moreover, wireless connectivity can be very lossy, bringing TCP, which reacts to stochastic losses as if congestion existed, to its knees. Current approaches require (usually application-level) coordination in order to fetch all data chunks from potentially multiple devices to complete a data transfer. A rarest-first approach is commonly followed (just like in BitTorrent) when deciding which data chunk to exchange so that the probability that a few (extinct or very rare) content chunks, which prevent the successful completion of content transmission, remains low.

In this paper, we deal with the challenges identified above by combining the Named Data Networking (NDN) [17] architecture and fountain coding [18,19], as follows:

- In NDN, communication is not based on end-to-end connectivity. Instead, the focus is on the content and routing is based on content names; therefore, topology changes do not result in broken connections that must be constantly rebuilt. In-network caching and multicast forwarding are inherently supported.
- In fountain coding, encoding symbols equally contribute to the decoding of the original content and, therefore, there is no need to retransmit lost data. Instead, the reception of new symbols will eventually lead to the successful decoding of content. Accordingly, there are no “rare” symbols that devices need to desperately keep alive in the network.
- With fountain coding, multiple sources (e.g., devices that can fetch data from the Internet or have previously cached encoding

symbols) can send symbols to a requesting device without any coordination among them. They only need to randomize the way symbols are created to avoid sending duplicate symbols.

- In fountain coding, there is no ordering of symbols; all received symbols decode the content (with some probability). Therefore, multiple paths can be used in multi-hop opportunistic networks. Receivers can also receive symbols of the same content from different network interfaces (e.g., Bluetooth and Wi-Fi).

In our approach, *Persistent Interests* (PIs) [20] (see Section 3) are forwarded (through scoped flooding [21]) to connected devices, requesting fountain-coded symbols for specific content. By employing scoped flooding of PIs at NDN's *strategy* layer [17] and fountain coding, we enable multi-source and multi-path forwarding. Additionally, we incorporate Bloom filters as part of the PI name [22] to minimize sending duplicate symbols from in-network caches (i.e., other mobile devices in the network) (see Section 3.2). Network dynamics (i.e., user mobility and frequent disconnections) are modeled by changing the set of devices that supply the network with newly requested content and by breaking already established connections among mobile devices.

The proposed approach successfully inherits the benefits of Information-Centric Networking, as realized by NDN [17], i.e., in-network caching and multicast, while at the same time it avoids redundancy associated with multi-source and multi-path communication in the considered environment, without necessitating any complex error control or source coordination mechanisms. The proposed solution, not only overcomes the limitations of TCP/IP, but also utilizes available resources more efficiently compared to its standard NDN counterpart, achieving higher cache-hit ratio and lower traffic overhead in the network. In particular, we observe that the usage of fountain coding can increase the cache-hit ratio by up to five times compared to the standard NDN [17], maintaining at the same time the overall traffic load of the opportunistic network in less than 25% of the load of the standard NDN.

2. Background

In this section, we briefly discuss relevant research regarding information-centric networking and fountain codes that forms the foundations of our work.

2.1. Information-centric networking

Internet usage patterns have been constantly changing over the last decades, especially after the wide adoption of smartphones, reaching a situation that was not foreseen when it was originally designed. The engineering principles underpinning today's Internet architecture were created in the 1960s and 1970s with the assumption that Internet would be mainly used for host-to-host communications. Differently, nowadays the vast majority of Internet usage is related to content distribution and retrieval and this trend is forecast to continue in the foreseeable future [23]. This has altered the network communication paradigm from simply routing packets between hosts (using endpoint addresses) to binding information producers and consumers together.

The mismatch between the original design assumptions (host- or node-centric) and the current usage patterns (information-centric) has been partially addressed through application layer, problem-specific solutions overlaid on top of IP, e.g., Content Distribution Networks (CDNs). However, the lack of native network support for content distribution restricts the efficiency of such approaches, and also potentially hinders the evolution of the Internet as a whole. This has created a trend towards content-oriented networking, which has recently been realized through the ICN paradigm. ICN puts content itself in the forefront of

¹ See <http://tinyurl.com/ogsz75o> as an example of a real world scenario.

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