Content Centricity in Constrained Cellular-Assisted D2D Communications

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Abstract. The huge increase of mobile traffic in the latest years has put cellular networks under pressure. To face this situation, operators propose to adopt data offloading techniques based on device-to-device communications to alleviate their infrastructure. In this paper, we consider a specific scenario in which the cellular channel has severe capacity limitations. Existing offloading techniques focus on the underlying communication mechanisms and fail to properly manage the interest users have in *content*. The straightforward approach to tackle this issue is to rely on the content-centric networking (CCN) paradigm. Nevertheless, the hybrid nature of our scenario makes this vision challenging—what should circulate through the cellular channel and what should remain within the opportunistic network? In this paper, we investigate our target scenario and identify a number of challenges therein. We finally define a high-level architecture that we intend to instantiate in the case of a public infrastructure scenario.

Keywords: Opportunistic device-to-device communications · Infrastructure wireless networks · Content-centric networking · Data offloading

1 Introduction

The advent of device-to-device (D2D) communication technologies has extended the traditional use of wireless networks, giving rise to new application opportunities. As co-located nodes may share common interests, an important communication functionality is *data dissemination*, in which a content must reach multiple destinations. Target nodes are said to be "interested" in the content while other nodes may play the role of relays to serve the target nodes. The bridge between those who generate the content and potential destinations falls within the scope of *publish/subscribe* systems that, when combined with a proper retrieval strategy, determine how efficiently content flows between publishers and subscribers.

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A challenge operators have to face in this context is the evergrowing increase of mobile data (mobile traffic is likely to grow about ten times by 2018, compared with 2013) [1]. Similar observations may also exist in Wi-Fi hotspots handling a large number of users [2]. Generally speaking, the main problem arises when *data transfer volumes go beyond the capacity of the infrastructure access*. Therefore, operators must either increase the capacity of their networks (and reduce their CAPEX/OPEX) or find some alternative ways to handle exceeding data traffic. At this stage, *data offloading* is foreseen as a promising solution to alleviate the burden on the wireless access infrastructure [3–7].

While existing data offloading solutions provide interesting strategies for routing and forwarding mechanisms, they neither consider how users access content nor what they are interested in. In this paper, we tackle this problem from the point of view of *content-centric networking* (CCN) [8,9]. The main idea behind CCN is to shift the network from the traditional, host-centric paradigm to content-centric operation. A content provider in CCN tags its content with a set of attributes and then disseminates it throughout the network. Subscribers interested in that content (or, more specifically, that share similar interests with regard to the content attributes) retrieve the content from the nearest node that has a copy.

The CCN architecture depends on information stored at nodes in the path between the sources of the content and the subscribers. For this reason, adapting the CCN principles to a case where nodes are potentially mobile is challenging. In our target scenario, where subscribers may either retrieve content from the infrastructure using cellular or Wi-Fi access or from other nodes using D2D communications, there is also the risk of overstressing the system with duplicated content and extra signaling traffic.

To achieve a good balance between functionality and efficiency, we focus in this paper on the possibility of designing a *lightweight CCN-based system for D2D communications under infrastructure assistance*. In our idea, since the infrastructure has a capacity-constraint channel, mobile devices have to explore that channel in a moderated manner. We take advantage of specific CCN features (e.g., naming and caching) to leverage the use of the infrastructure as a control support and keep, whenever possible, data in the opportunistic domain. To the best of our knowledge, there are no equivalent approaches specifically designed to the case of mobile opportunistic traffic offloading.

The remainder of this paper is organized as follows. In Section 2, we describe our target scenario where device-to-device communications are supported by a (capacity-constrained) cellular network. In Section 3, we highlight the main architectural features of CCN that seem to be relevant to the context of offloaded D2D content delivery. In Section 4, we investigate how to adapt those features to address the challenges arising in the context of D2D communications. We identify a candidate high-level architecture for our framework in Section 5 and conclude the paper in Section 6.

2 Constrained Cellular-Assisted D2D Communications

The area of traffic offloading has recently generated intensive research activity. Yung et al. classify offloading mechanisms in three categories [10]: (i) broadcast offloading [11], where the infrastructure uses broadcast to reach all users within a cell, (ii) Wi-Fi offloading [5,12,13] that leverages the availability of Wi-Fi access points to mitigate traffic on cellular networks, and (iii) opportunistic offloading [3–7], which exploits device-to-device opportunities to reduce the traffic in the cellular network. In this paper, we are particularly interested in opportunistic traffic offloading.

We consider a system where nodes are, at all times, covered by some sort of wireless infrastructure (e.g., cellular, Wi-Fi). This means that they have permanent access to the Internet. We assume that nodes may bypass the infrastructure and communicate directly in a device-to-device way. In our target scenario, the access channel of the infrastructure is likely to be *highly constrained* with regard to its capacity. The limitations may be due to contention for resources (e.g., due to data avalanche or poor wireless conditions) or to some operational rules. This latter case is of particular interest to our work, as it corresponds to our case study (see Section 5). In a nutshell, this case study is a public service where cellular or Wi-Fi hotspot operators reserve a thin share of their capacity to provide a low-rate, open channel for citizens. These latter have then a minimal possibility of connectivity, even when they are covered by a different operator than her/his (in an equivalent way to emergency numbers that citizens can call even if she/he roams or has no credits available).

We illustrate our system in Figure 1. As we can see, the infrastructure must push the content to at least one of the users that can then rely on device-to-device communications to retrieve the content. As a design principle, we assume that one bit transferred in device-to-device mode costs much less than one bit downloaded from the infrastructure. Although there are some adversaries to this assumption (e.g., battery consumption at devices), it seems to be a good approximation for the purposes of overall capacity improvements [14].

Since interactions between mobile users and their content providers (e.g., through the cellular infrastructure) increase as much as users ask for the content, deciding what and when to offload is an objective of a paramount importance. In other words, we need to find new ways to satisfy users' needs while respecting the constraints of the cellular infrastructure. We believe that the CCN paradigm brings a number of features that fit well our context, which does not come at free, as adapting the CCN architecture to the case of mobile nodes is not straightforward[1].

[1] Although several papers in the literature have considered this problem in the case of pure ad hoc or opportunistic networks, little attention, if any, has been paid to the case of cellular-assisted mobile networks.

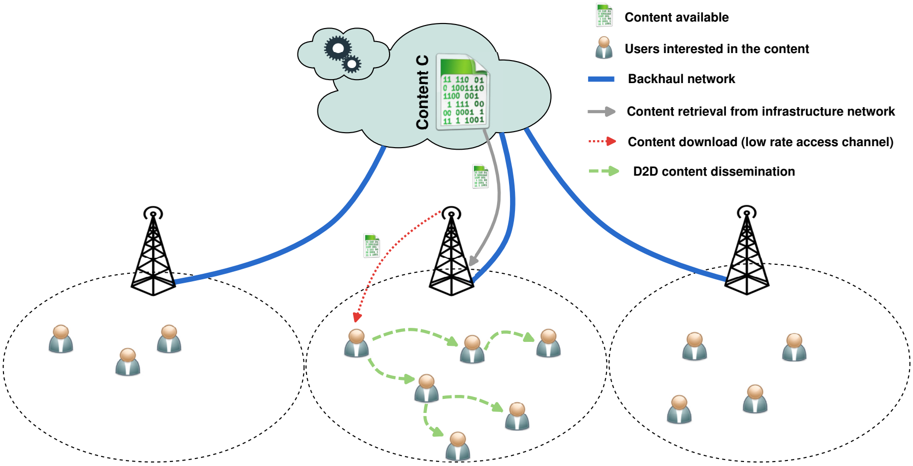

Fig. 1. Offloading scheme. Note the bottleneck due to the limited capacity of the access channel.

3 Accessing Content in Constrained Cellular-Assisted D2D Communications

Common offloading policies that can be found in the literature are mainly based on the analysis of users' mobility patterns [15]. We propose to extend these policies by considering the content itself. The idea is to provide the ability for users to benefit from the availability of content in their vicinity to avoid consuming unnecessary infrastructure resources.

To this end, we investigate the paradigm of content-centric networking (CCN) as a way to leverage on content availability resulting from replication or caching. Content-centric networks have attracted huge interest from the research community leading to the proposal of several architectures following popular designs [16–18]. Motivated by the ability to access content in a location-independent manner, the common underlying paradigm to these architectures calls for a shift in the way communication takes place among network entities since the emphasis is on the content rather than the location. According to this paradigm, a piece of content can be retrieved without relying on the binding of the corresponding data object to its host location. The practical purpose shared in the design of content-centric networks is to meet the data-intensive application needs by improving content delivery performance and reducing traffic overhead. In the following, we choose CCN as a reference architecture [9] and present its main features that, we believe, are the most relevant toward efficient D2D offloading.

3.1 Content-Centric Networking Background

The CCN proposal has gained much attention from the research community [9]. Instead of replacing IP with a clean-state approach, the CCN design follows a

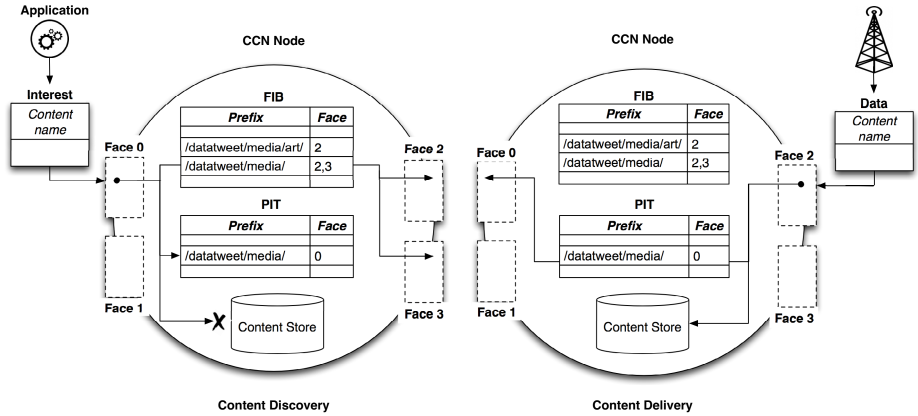

Fig. 2. CCN communication framework

more conventional approach—it aims at showing that removing IP addresses from the Internet does not call for revisiting IP engineering principles. The key objective is to investigate whether the Internet can evolve from a design that has been exclusively host-centric to a content-centric paradigm. As a result, the key choices that have driven the design of CCN were taken to enable the reuse of well-tried mechanisms and techniques borrowed from IP.

As depicted in Figure 2, a CCN communication consists of two phases: content discovery and content delivery. Content discovery uses Interest messages that contain the CCN content name. They are handled in a way that depends on a strategy layer. A strategy defines on which interfaces, also called "faces", a CCN node will forward an Interest. Broadcast is one obvious strategy that can help foster content availability. Carefully designed strategies may be relevant in the context of D2D communications as the list of faces can be seen as the multiple contemporaneous connectivity opportunities. In response to the Interest message, every node that holds a copy of the requested content returns a Data message. Multiple Interest-Data exchanges may be required to complete a request for a content divided in chunks (as the requester may receive each chunk from different sources in parallel).

The CCN node model includes three key data structures depicted in Figure 2, namely the FIB (Forwarding Information Base), the PIT (Pending Interest Table), and the Content Store (buffer memory). The first two structures specify how to process Interest and Data messages, respectively. A FIB entry is defined for a given content and indicates the list of faces pointing towards the content source(s).

PIT contains the list of interfaces on which Interest messages for the same content are received before forwarded upstream, towards the content source(s). Unlike the Interests that are routed according to the FIB, Data messages are returned to the requester by simply following the chain of PIT entries left by the Interest(s) back to the requester. The advantages of PIT is two-fold: PITs avoid loops by propagating multiple instances of the same Interest messages. PITs also allow aggregation of multiple similar Data messages since only one is expected to flow back to the content requester.

The Content Store is used as a cache memory where Data messages are stored on their way back to the content requester. Since content can be accessed in an application-independent way, in-network caching allows every node to be turned into potential content sources by intercepting Interests on their way to the original upstream content source. As so, the content store increases the access efficiency by minimizing the retrieval time and maximizing the upstream bandwidth demand.

4 CCN-Based System for D2D Communications Under Infrastructure Assistance

In the previous section, we have highlighted the main architectural features of CCN that are relevant in the context of D2D traffic offloading. We now investigate how to adapt those features to address the challenges that arise in the context of D2D communications offloaded from a cellular-based infrastructure network. We conclude that some of the CCN key design choices are well suited for enabling resilience to episodic content availability due to hosting node mobility or network failures.

4.1 Naming

The CCN name syntax is inspired by the naming scheme of DNS. Whereas DNS specifies rules for delegating assignment authority over global names, CCN is interested in the support of prefix aggregation enabled by the hierarchical structure of domain names. CCN applies the concept of aggregation introduced by CIDR to the context of URL-based content names. From the use of aggregation as an already well-tried technique, it is expected that routing and forwarding for CCN can achieve scalability.

Instead of DNS-based names, flat namespaces appear to be a better candidate in the context of an opportunistic network. A flat namespace consists of unstructured, location-independent, and human-unreadable identifiers. Flat names are said to be semantic-free since they provide the ability to refer to content and services independently of the hosting endpoint, regardless of its administrative domain, location, or network topology. In contrast to the DNS-based names, content can be replicated or move with their hosts while avoiding broken links or using HTTP redirection, which requires excessive control overhead and increases latency.

A flat name might be a long sequence of bits chosen randomly (typically 128-bit long). It can be derived from the cryptographic hash of the public key of the content owner (for authentication) and of the content itself (for integrity). The granularity of naming is flexible since a name can refer to a host, to a content, or, at finer granularity, to any content item with no reference to the hosting endpoint. At the user-level, it is assumed that a mapping service provides applications with the names corresponding to human readable descriptors such as search keywords.

It might be also relevant to consider the hierarchical structure of cellular networks, especially if the content depends on location and time information, which is also true for contextual content generated by applications with high spatial significance. Content names may include information regarding the location where content is generated or has relevant meaning. Location information allows the use of geographic routing for contextual content discovery.

4.2 Content Discovery and Delivery

In CCN, content discovery uses Interest messages. CCN Interest forwarding relies on FIBs that contain the list of interfaces pointing towards the content sources. FIBs should result from a routing protocol. Routing is and remains, however, a critical area of investigation for CCN as none of the existing proposals has prevailed yet. Proposals exist for the Internet and connected MANETs as they assume end-to-end connectivity [19–21]. Moreover, the paradigm of store-carry-and-forward cannot be directly borrowed from DTNs and applied as is to CCN since the location of the requester is not exposed in the Interest messages during content discovery.

Adapting CCN to the context of opportunistic networks can benefit from the strategy layer that specifies how Interest messages should be handled. As stated previously, a strategy defines on which interfaces a CCN node will forward an Interest. In the context of our reference architecture, the interfaces of a node refer to its connectivity opportunities such as 4G or Wi-Fi. Broadcasting an incoming Interest on all of the interfaces listed by the corresponding FIB entry, is one obvious strategy, but too costly to be adopted. Instead, a CCN node can use more efficient alternatives—we advocate for an implementation of the strategy layer where decisions are taken based on users' preferences and content properties.

The analysis of users preferences can help to detect communities as a way to efficiently deliver content to users using opportunistic contacts [15]. If users interested in the same piece of content show strong spatial locality, CCN Interests can be rerouted from the base station to the neighboring nodes who already retrieved the content earlier. To maximize the benefit of D2D communications, the base station keeps track of the users in its coverage area and decides to broadcast the requested content with respect to the content time constraint. Users can take on the responsibility of transmitting the content to other users in the same community located outside the coverage range of the base station. It may also be worth applying social-based forwarding by ranking community members according to social metrics such as centrality that measures the importance of a node in a network [22]. Interest messages are forwarded through the most popular nodes within the community until the messages reaches a content source.

The characterization of content includes the analysis of popularity distribution and the spatial significance and temporal availability of each piece of content. Content identified as popular is likely to be available in the content store of devices close to the user. Redirecting Interest messages from the infrastructure network toward neighboring nodes makes it much cheaper and faster to access popular content locally. To maximize the benefits of cooperative caching among nodes, heuristics need to be defined so as to select content items to be cached based on the distribution of content popularity. The CCN content store may be used for carry-store-and-forward scheduling by assisting nodes as they can make content available for users on the move while avoiding those users from overloading the infrastructure network. By increasing the availability of less popular content, caching strategies can help nodes bring content in a closeby neighborhood to the interested users for eventual delivery. Content replication strategies driven by the base stations can also be used to further increase less popular content availability to the interested users.

5 High-Level Architecture and Target Use Case

We propose a high-level architecture that covers the requirements and issues discussed in this paper. We do not intend to design the ultimate solution, but only to identify the best possible directions to exploit in a future implementation of the system.

5.1 Architectural Elements and Modules

As depicted in Figure 3, the architecture includes four main modules that we detail in the following. Each module is in charge of several tasks shared among sub-blocks that focus on specific functionalities.

1. **CCN Engine.** This module is responsible for managing the data crossing a mobile node. It is composed of three sub-modules. The *content store* block plays the role of a cache for incoming data messages on both "local" and "public" caches. The PIT manager keeps track of pending interests that have not yet been satisfied, while the FIB manager keeps track of the outgoing traffic on the different faces (as detailed in the CCN main functionalities).
2. **Network Controller.** It defines the interactions with the other entities in the network and encompasses three sub-modules: *interest manager* and *content dissemination* are respectively in charge of controlling the outgoing interest list and incoming data messages, as well as for checking whether they respect the proposed strategy. The last sub-module, namely *neighborhood monitoring*, manages the direct device-to-device communication opportunities.
3. **Surety Module.** This module is in charge of security operations to ensure content integrity and avoid any falsification during the data exchanging process among mobile nodes. The *interface switching* sub-module reports to

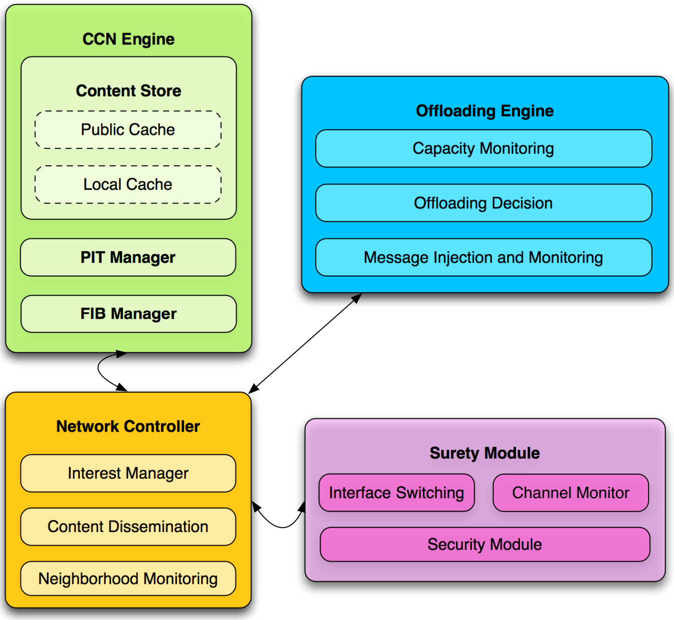

Fig. 3. High-level architecture for the CCN-based data offloading scheme

the node when the infrastructure has performed a vertical handover; in this way, the node can receive the content from the second interface. The *security module* that deals with privacy concerns supervises this latter process. Finally, since the infrastructure is capacity-constrained, monitoring the channel evolution is mandatory to avoid any wireless link congestion or saturation between nodes and base stations—this is performed thanks to *channel monitor* sub-module.

4. **Offloading Engine.** Last but not least, we need a module to focus specifically on the offloading process. One of core functionalities of our system is the decision of whether a given content must be exchanged in an opportunistic way or not; indeed, the overhead generated by offloading signalling messages must be compensated by a reduction of data messages traversing the cellular channel. The offloading module comprises a *capacity monitoring* tool, an *offloading decision* sub-module, in charge of determining whether the offloading is worth triggering, and a *message injection and monitoring* functionality that checks whether the offloading procedure evolves or not.

5.2 Target use Case: DataTweet Public Open Service

DataTweet is a recent French-funded project that proposes to explore the idea of an ubiquitous public data service for transmitting short messages in a similar way to Twitter [23]. Any user or source of the service will be able to send a short message at a very low rate to some destination address over various access networks: open 802.11 hotspots, base stations of LTE, car-to-infrastructure stations of 802.11p, to cite a few. Moreover, it defines a free public channel that could be used by crowds of devices to send their data towards their destination. Devices in DataTweet are supposed to be connected either via an infrastructure (i.e., access points) or together in an opportunistic way, where devices could leverage their contacts opportunities to mitigate the infrastructure load.

In a similar way to the water cycle, crowds of devices and mobile users may generate data sent to the cloud through nearest access points like water evaporating to the sky to form clouds. Collected data become useful information in the cloud, because of all the meaning and interpretation that we can attach to raw data. Then, the cloud can shower the users and devices with the information transmitted in short messages in target areas.

Our work perfectly fits the requirements of the DataTweet project. In fact, the cloud must be careful when deciding to whom content should be sent, as the system may easily diverge from a reasonable operation point. The CCN approach we advocate is expected to address the multiple issues that arise in our target scenario.

6 Summary and Outlook

The main contribution of this paper is to identify and discuss the challenges and promising solutions to address content management in capacity-constrained cellular networks. This is a particular scenario that requires specific solutions that cannot be directly adapted from the well-established, recognized content-centric networking (CCN) paradigm. Achieving efficient data offloading in such a hybrid context requires adapting some functionalities (e.g., naming and caching) to the case where nodes are potentially mobile. As the first solution to this problem, we have proposed a high-level architecture to cope with the unbalanced nature of the network while keeping the main principles of CCN.

Good understanding the new network architecture is the key function that opens several research tracks and a lot of directions to explore. What we consider very important is the development of a real system based on the proposed architecture. To this end, we propose to consider the ANR DataTweet scenario as our substrate case study. As the project has just started, we expect to obtain motivating results in the near future.

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