Towards Decentralized, Energy- and Privacy-Aware Device-to-Device Content Delivery

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Abstract. Device-to-Device (D2D) content delivery is a new approach to directly exchange content between mobile devices, which allows to offload traffic from infrastructure-based networks and thus reduces the risk of congestion. While centralized D2D approaches rely on the mobile operator to discover nearby devices and initiate a content transfer, in decentralized D2D the devices autonomously and opportunistically organize themselves to deliver content to each other. The latter approach is more flexible as it does not depend on a single operator, however, it typically requires more energy for scanning other devices. Another issue is privacy, since the decentralized approach reveals a user's interest for content to all devices in proximity. Therefore, this paper sketches an new approach towards decentralized energy- and privacy-aware D2D content delivery. The proposed approach addresses the energy loss that occurs when constantly and spontaneously scanning multiple unknown devices for content. Furthermore, the paper identifies privacy requirements and proposes first steps towards a privacy-aware D2D solution.

Keywords: Device-to-Device, Content Delivery, Privacy, Energy, Decentralization, Delay-Tolerance, Opportunistic Networking

1 Introduction

As people are sharing more higher-resolution multimedia content, traffic demand in the Internet is constantly increasing. Today, content is transferred mostly from a content provider's server to a consumer's device. Different types of content delivery can be distinguished: *Live* content is immediately consumed after creation, including a short transmission delay. *On-Demand* delivery refers to content that is commonly consumed an arbitrary but significant amount of time after creation, whenever a particular consumer requests it. For example, most of the web content is delivered this way. *Video-on-Demand (VoD)* services deliver movies and video clips on request, which are typically very bandwidth-intensive. Although less bandwidth-consuming, music, applications and software updates are also content types appropriate for on-demand delivery.

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Delivering copies of content to a large number of receivers is challenging in terms of network load. Many carriers use IP Multicast to deliver live content to their own customers. However, in the current public Internet, multicast is not widely implemented between carriers. For on-demand content delivery, multicasting is not applicable, as content has to be delivered to every consumer by the time of request. Content Delivery Networks (CDNs) place replica servers in proximity of the access network, which offloads the content provider's uplink and inter-carrier transits. However, the consumer's access network itself is typically not affected by the traffic reduction.

Device-to-Device (D2D) content delivery transmits content from a consumer's mobile device directly to another one in range. This way, infrastructure utilization is reduced especially for the transfer of popular content in crowded areas. Also, the quality of experience (QoE) can be increased in case of bandwidth-limited infrastructures. D2D content delivery only is effective if a certain device density and content popularity is given. If there are few devices in range or the content is unpopular, chances are high that there is no device in range serving the content. D2D content delivery mechanisms can be distinguished by the type of content *discovery* mechanism used.

Centralized D2D content discovery [1] [2] [6] relies on the cellular operator locating content in range and triggering the transfer between devices. For that, an operator requires data like the position as well as information about available and requested content. In contrast, a *decentralized* [10] mechanism lets the devices organize the discovery and transfer of relevant content themselves. Such an operator-independent service, when standardized, is available to and communicates with every device, not only the devices under contract with the operator. Furthermore, it can even work in the absence of a mobile infrastructure.

However, current link-layer protocols widely implemented in consumer electronics (e.g., IEEE 802.11 [7]) are focused on low-delay and reliable communication between devices previously known to each other. Using the default 802.11 MAC layer, discovering content on any device currently in range involves an exchange of multiple management frames and unnecessarily frequent medium listening (ATIM window), leading to an increased energy consumption. Additionally, requesting content by broadcasting leads to an unintended disclosure of user interest to all devices in communication range. Attackers may also flood requests for privacy-sensitive content and track devices answering it. Previous approaches did not investigate how these issues can be mitigated, except that they switched to a centralized, operator-dependent solution [1] [2] [6].

Based on this finding, the goal of this work is to propose a new operator-independent approach towards D2D content delivery between mobile devices, while addressing energy-efficiency and privacy, starting at the link layer. The remainder of this paper is structured as follows. In Section 2, a modification of the 802.11 data link layer for energy-efficient, opportunistic content discovery is sketched. Also, the aforementioned privacy concerns are addressed and first countermeasures are proposed. Moreover, Section 3 discusses related work, while Section 4 concludes this paper.

2 Energy- and Privacy-Aware Content Discovery

The proposed discovery mechanism follows a single hop D2D approach. While content delivery can also be done over multiple hops, for the purpose of stability, medium availability, energy conservation, and the lack of incentives for intermediate nodes, this approach is not considered here. The discovery mechanism involves two roles, a content requester (CR) and a content provider (CP), where a device can take both roles at the same time. The CR maintains a predicted table of content identifiers likely to be consumed in the future, while the CP maintains a cache of provided content. Prediction and caching strategies are not part of this paper.

As the devices are previously unknown to each other, they communicate by broadcasting link-layer frames in their proximity, either content requests (active) or content advertisements (passive). The frames contain a list of content identifiers. To be able to receive each other's frames, devices must agree on certain physical parameters like the 802.11 channel and rate, which may be done at roll-out time. In order not to drain the battery, the opportunistic broadcast mechanism works without any previous device scanning, participating in distributed beaconing, or handshake. Instead, a broadcast is only answered by CPs providing (active) or CRs requesting (passive) the particular content, other devices remain silent upon reception. This certainly involves changes in IEEE 802.11's MAC Sublayer Management Entity (MLME) [7]. The changes must not interfere with standard 802.11 operation.

Conserving energy also incorporates the decision when to power on and off the transmitters, referred to as *sleep scheduling*. Increased wake-up intervals and smaller wake-up periods may conserve energy, but also increase the delay as messages have to stay longer in the buffer to wait for the next wake-up. Fortunately, such a wait-to-send delay in the area of seconds is not a concern for decentralized content discovery. Instead, finding a good way to synchronize these wake-up periods between devices that are spontaneously in contact to each other is a major challenge. An approach suitable to this problem would lead to synchronized listen-sleep periods as depicted in Figure 1.

To increase privacy of the discovery mechanism, two approaches are proposed. First, a clear-text identifier is replaced with a hash-salt combination, where the salt changes in every request. This way, only devices in possession of the content identifier understand the request. Secondly, the usage of anonymous addresses in wireless media hardens the tracking of devices. Therefore, MAC addresses used for opportunistic requests can be randomly chosen and frequently changed.

3 Related Work

Golrezaei et al. [6] investigate an approach for distributed caching. Although they first propose to establish femtocells controlled by small base-station-like nodes called *helpers*, they later consider a pure D2D communication system where the mobile devices play the helper role themselves. In the latter, the D2D exchange

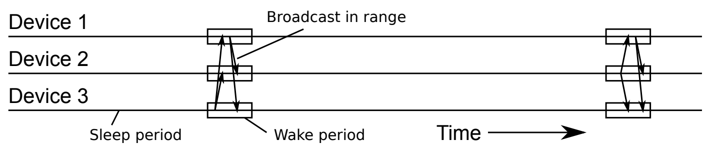

Fig. 1. Expected result of sleep scheduling for broadcast messaging. Devices power on at the same time, broadcast content requests in this time window and power off again.

is completely controlled by the operator, which knows the device's position, as well as the content that is currently cached by every device.

Bao et al. [1] [2] propose a centralized mechanism, where the network operator tracks the location of mobile devices. The operator then identifies areas with a high device density (data spots). Whenever a certain density is given, content requests are mediated by the operator, which initiates a WiFi connection between the requester and a device in proximity having the desired content.

An approach for decentralized content discovery was proposed by Ma and Jamalipour [10]. Evaluated costs are focused on bandwidth consumption and disk space. Nevertheless, optimizing energy consumption was not addressed, although this has been done for Bluetooth [12] [5].

Boldrini et al. [3] exploit a user's social relationship to decide where to place content. Cost evaluations concern limited bandwidth and cache. Distributed sleep synchronization for energy conservation in MANETs has been addressed by Jiang et al. [8], as well as Choi et al. [4], but these approaches are not focused on broadcast discovery between devices previously unknown to each other.

In the area of privacy, much research has been done and is underway in the area of opportunistic networks (ONs) [9], but regarding *content delivery* in ONs, very few exist. Privacy was addressed by Shikfa et al. [11], given prior key distribution and using intermediate nodes.

4 Summary and Future Work

In this paper, a new approach towards decentralized D2D content delivery has been proposed. The operator-independent approach shows clear advantages as it even works in the absence of an infrastructure. Moreover, the paper sketched a solution how energy and privacy issues can be mitigated.

To identify the situations in which D2D content delivery is effective, likely urban environments with a high device density and providers of popular content, request and position traces of a large cellular operator will be evaluated. In addition, user incentives for *providing* content via D2D communication have to be provided. Mechanisms to measure D2D contribution and possible rewards have to be designed. Furthermore, the approach sketched in Section 2 will be further developed to a complete protocol. The last steps towards a solution include an energy- and mobility-aware simulation and a prototype implementation. In parallel, social-content interdependencies and their exploitation will be investigated.

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