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Content Wanted: A Different Shade of D2D Communications

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***Abstract*—One of the emerging topics in wireless networking is user-to-user, or, as it is often referred to, device-to-device (D2D) communications. Several technological solutions already exist, or are under development, so that D2D links between fellow users can be efficiently created. In this paper, we highlight a different, yet fundamental, aspect for the wide adoption of this new communication paradigm. We argue that D2D data transfer will become commonly employed if it can successfully provide users with the content, or service, they are looking for. We therefore advocate the need for innovative caching and advertisement strategies, as well as for techniques that allow users to select those wireless links that can actually help to get them what they want, with a satisfactory level of QoE.**

I. Introduction

The management of mobile users and the satisfaction of their requirements in terms of quality of experience (QoE) are major technical challenges that we are facing in wireless networking [1]. The relevance of these issues is destined to increase as traffic generated and consumed by mobile users is expected to reach 90% of global user traffic by 2017 [2].

In order to address the above problems, let us stand back and observe what is going on in the real world. Three facts strike our attention.

(i) Each user typically owns a number of communication devices of various types (e.g., smartphone, tablet, laptop), and the current trend seems to lead to an increase of such number.

(ii) User devices are now full-fledged entertainment stations, and their owners require high-quality multimedia content and services, such as multiplayer gaming and video delivery [3].

(iii) Users are hyperconnected. As shown in Figure 1 (left), not only they may be under the coverage of several wireless network technologies, including 2G/3G/4G and Wi-Fi, but they may also transfer data through D2D communications [4] like Wi-Fi Direct or Bluetooth. Indeed, while it is true that mobile ad hoc networks (MANETs) have not played so far a major role in the mobile networking scenario, a new trend is emerging thanks to the increasing popularity of smartphones and tablets [5].

On the one hand, such a rich scenario offers a plethora of social, economic and technical opportunities; on the other, it requires some optimization, at best.

In this paper, we carefully look at the above scenario and sketch a possible path toward an efficient exploitation of the available communication opportunities, while highlighting a number of exciting research lines. In particular, we claim that users should be able to enjoy the desired level of QoE, independently of where they are or the type of device they carry. Also, whenever possible, connectivity offered by D2D communication should be exploited as it brings significant benefits to both users and mobile operators. To users, as it represents the most convenient way to receive a service or content in terms of monetary cost and energy consumption. To mobile operators, as it is an effective way to offload the network infrastructure, extend the cellular coverage and facilitate new types of wireless peer-to-peer services. This calls for a new concept of user connectivity that encompasses different network technologies and use them in a synergic manner. Clearly, at the center of this innovative concept there are the users and the content/service they request. That is, the selection of the available connectivity opportunities and their integrated usage should be driven by: (1) the *user profile*, including its mobility characteristics, battery level, monetary costs and QoE requirements, and (2) *what* content or service the user is looking for and *where* it can be found. The latter in particular is paramount to the decision process. In fact, as depicted in the right image of Figure 1, only those communication nodes (Wi-Fi access points, cellular base stations, other user fellows) that can provide the requested service/content are eligible communication end points for the user.

The remainder of this paper is organized as follows. We describe our vision and introduce the main concepts at the basis of the proposed network paradigm in Section II. Then, we detail the necessary steps for implementing such paradigm in Section III. Further technical challenges related to user incentives and connectivity selection are discussed in Sections IV and V. Lastly, Section VI concludes the paper and points to possible directions for future research.

II. Users and content: The essential components for a new connectivity paradigm

In order to let users fully exploit today's hyperconnected environment, a new networking paradigm is required that selects the best connectivity mode(s) for the user.

What *best* means clearly depends on what users want and on the conditions under which they operate. As an example, to a user aboard a vehicle and downloading a video streaming, cellular connectivity may be the best choice as its extended coverage makes handovers less frequent in spite of the high user speed. Instead, a pedestrian looking for the web page of TripAdvisor that suggests amenities in the close-by area, may find more convenient to retrieve the content using D2D communication, which is particularly attractive due to its reduced monetary and energy cost. Similarly, users wishing to download a popular video may prefer to get it at low cost using a D2D data transfer.

Ideally, most of the user profile information (such as mobility and battery level) could be automatically acquired by the communication device, without requiring human intervention. Other information can be input by the user itself once for all, e.g., preferences on the tradeoff between connection monetary cost and level of QoE that can be obtained. Then, upon a user request for a content item or a service, the device (e.g., the smartphone) should autonomously take the best connectivity decision for the user.

One important point that deserves additional discussion is the practical feasibility of a user being served through D2D communications. Although ad-hoc WLAN mode has been available in 802.11 for many years, in practice its usage has been very limited compared to the infrastructure mode. Nevertheless, several other technologies exist, or are under development. Think of Bluetooth or Wi-Fi Direct communication interfaces: the former is embedded in all mobile devices, while the popularity of the latter is steadily increasing [6]. Visible light communication (VLC) is another promising networking solution [7], [8], which is still in its infancy, as LTE Direct, i.e., D2D communications in LTE-A over licensed band [9]–[11]. Thus, establishing D2D wireless links is not expected to be an impairing issue. Furthermore, solutions like LTE Direct could be exploited to assist users with issues like peer discovery, synchronization, and the provision of identity and security information [10], [12].

One major impediment to serving a user via D2D communication is instead related to the availability of the requested service/content. As an example, let us focus on information content queries. Clearly, a request can be satisfied through D2D if the following three conditions are met:

(i) the desired content is stored by a user device in the proximity of the requesting user and the content is successfully discovered;

(ii) the user storing the content is willing, or finds it convenient, to provide the content;

(iii) D2D connectivity can satisfy the user requirements in terms of throughput so that the expected level of QoE can be guaranteed even in presence of bandwidth-hungry applications.

Ensuring the above three conditions is not trivial. Strategies for content caching, discovery and advertisement have to be developed so as to ensure that content is found in the user proximity with high probability, while keeping the procedures overhead low. However, users will never cache content for others, or provide fellow users with the content they own, unless they are motivated through proper incentive schemes. Link characteristics, as well as their suitability to meet the user requirements, should be carefully evaluated before a connection is created. In case it is convenient to establish parallel connections (e.g., when a single D2D link is unable to provide the desired throughput), the latter should be properly handled and traffic split over them.

In the next section, the above aspects are further investigated, highlighting some major research challenges.

III. Content Orienteering

The orienteering sport is a good analogy for the approach that should be adopted for finding a content item in a D2D network, characterized by fleeting connectivity, sudden topology changes and dynamic content availability. Below, and in Figure 2, we outline the main functionalities that a D2D network system should embed, in order to let users find what they are looking for.

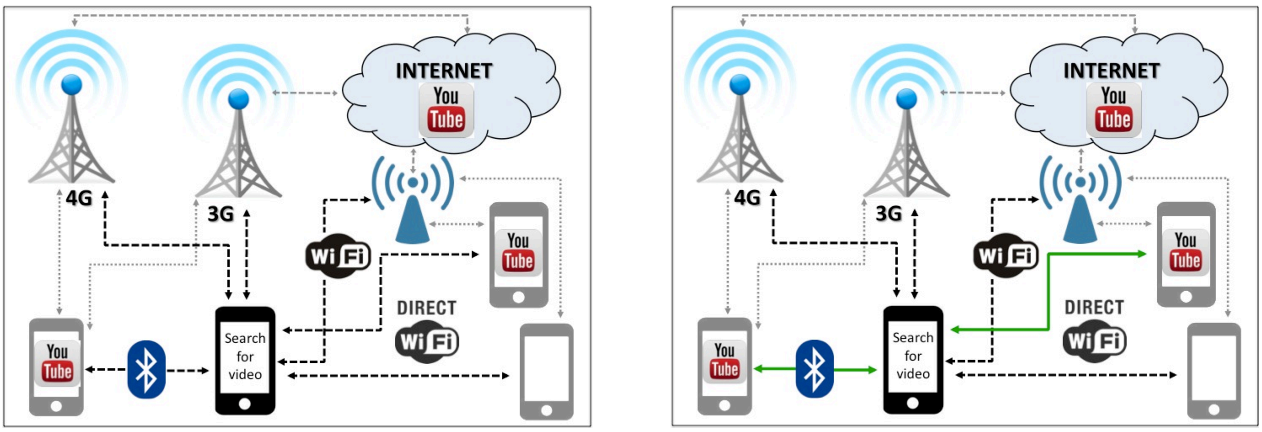

Fig. 1. Left: A hyperconnected scenario, where several possible connectivity opportunities are available to users. Right: Green lines denote wireless links with eligible communication endpoints.

Fig. 2. System functionalities needed to enable content orienteering and efficient data delivery in a network based on D2D communications.

A. Content caching

Content caching is crucial for both infrastructure- and D2D-based communications. In the first scenario, the fact that base stations or Wi-Fi APs cache popular content, or prefetch content by predicting the user demand, sensibly contributes to reducing user access to Internet servers, hence to avoiding traffic congestion on backhaul links. In the second scenario, instead, content caching (preferably implemented through distributed strategies) is a necessary condition to benefit from D2D communications.

Here we focus on the D2D scenario, and we slightly abuse the term caching to refer to both content caching and replication [13]–[15]. The latter is, in principle, a different concept, as it relates to the problem of defining how many copies of a content item should be created and at which communication nodes, rather than to determining which content should be stored by the devices.

Several caching strategies have been proposed for vehicular [16], or opportunistic networks [17]. Such schemes account already for content popularity and user profile information, like mobility, energy capabilities or social interactions. However, ways in which caching can be employed to extensively exploit D2D communication have still to be explored. In particular, in order to be effective, caching should primarily leverage the prediction of content demand of the single users, or of user categories, i.e., users with similar behavior and operating in similar conditions. This task has not been fully addressed in the literature yet. There exist techniques that estimate the type of application that users may request in the future [18]–[20], but a great deal of research is still needed to reliably predict the content that users will ask for, given their profile.

Assuming that user content demand can be predicted, user devices should acquire information on the geographical area where they are, what content is currently stored there as well as their neighbors and what they are likely to request in the future. In a nutshell, following the principles of orienteering, users should learn the characteristics of the environment where they are operating. Such knowledge can be then exploited to determine what the devices should cache to meet the local demand and effectively exploit their distributed storage capabilities in a coordinated manner [21], [22].

B. Content advertisement and discovery

Any content a user device can provide should be advertised to fellow devices, i.e., to potential requesters. Several schemes have been proposed for service provisioning, including publish/subscribe [23] and social-behavior-based strategies [24]. Clearly, both single- and multi-hop communication can be exploited, depending on where the content is located.

Most of the existing solutions rely on the fact that users wishing to advertise the content they own send advertisements, while users interested in a content send query messages. Advertisements and queries propagate through the network, collecting the id of the traversed devices. When a query hits the information related to the desired content, the latter can be retrieved from the source and delivered through the same path traveled by the query message.

As simple as it sounds, the above procedure has to be carefully designed in order to keep the overhead and the content discovery delay limited. Firstly, for each request there may be several user devices that can provide the content. Secondly, the network topology is often and rapidly changing, and devices are expected to own local knowledge only (i.e., related to their one- or two-hop neighborhood). Thirdly, each hop performed by an advertisement or a query message has a cost in terms of radio resources, channel congestion and energy consumption, beside leading to longer latency. However, any additional hop may be crucial to finding the requested content. Thus, how far and over which directions advertisement and query messages should spread are important questions that we need to answer so that an optimal tradeoff between the aforementioned factors can be established.

IV. Incentives to Cooperation

For several years researchers have analysed cooperation in ad hoc networks. Indeed, it is paramount to the efficiency of such systems that devices devote part of their bandwidth and energy resources to handle data traffic for others [25], and part of their memory to store content that may be needed by others [26].

Among the available solutions, of particular interest is content trading – a concept that has been proposed in the context of wired networks [27] but that can be successfully applied to D2D scenarios as well. The idea draws on the economic finding that bilateral content exchange is hard to achieve, due to the unbalance between users that request and those that possess a content item. There may be many users searching for an information item and many that own it, however a perfect coincidence is rare to occur. In economics terms, this matching of interests is the basis of the barter system, whose logistical inconvenience was overcome by the introduction of money. Similarly, in networking, virtual currency has been widely adopted to facilitate user cooperation (see, e.g., the pioneering work in [28] or the Bitcoin system [29]).

Here, we argue that the use of real money could become an effective way to promote content caching, advertisement and delivery in D2D communication networks. Innovative business models could be developed, so that a user will find it convenient to download, or create, content that may not be of interest to the user itself but from which it can obtain a profit when the content is sold to others. Similarly, users could "lease" part of their memory capabilities to cache content for others, or, upon a monetary reward, act as relays and download from the network infrastructure content of interest to fellow user devices. Once a user enters its preferences about content, memory and connectivity bargaining, novel applications can be developed that automatically trade the device capabilities and content items, thus promoting cooperative caching as well as content and connectivity sharing.

V. How to get content delivered to you?

Now assume that a user has requested a content item and that its device has identified more than one fellow device as possible content source. Then, as depicted in Figure 2, the main question becomes from which of these sources the content item should be retrieved. As mentioned, the user profile, along with the characteristics of the available communication links and of the desired content, are critical to such decision. While the user profile, content size, or requested bit rate can be easily acquired, estimating the links characteristics is much more challenging, especially if they are not currently under use.

Important metrics that characterize a D2D link are power cost, radio coverage and available bandwidth. The link power cost relates to the power that should be irradiated by the user device in order to reach the fellow device, as well as to that consumed by the device radio interface (e.g., Wi-Fi Direct, Bluetooth). The first is a time-varying quantity that can be estimated based on: the current position of the users, their expected mobility, and the information available on local propagation conditions. If the link has been used recently, history data on the level of irradiated power can also be exploited. The second contribution, instead, is due to the power consumption of the user radio interface in different operational states (e.g., transmit/receive/idle/sleep). This quantity is technology dependent and can be measured through existing tools, like the Monsoon power monitor for smartphones.

The radio coverage provided by a D2D link and the available bandwidth it can offer are strictly related to the user QoE. Indeed, jointly considering the link radio coverage, the users position and their expected mobility allows an estimation of the connectivity disruptions that will take place during the user service time. The link radio coverage depends on several factors, including the networking technology under use, the level of power irradiated at the antenna, the radio propagation conditions and the transmission data rate. Its prediction therefore requires propagation maps as well as history of previously used power levels and data rates per communication interface. With regard to the available bandwidth over the wireless link, its estimation is a fundamental step to evaluate the throughput that the link can offer, hence its suitability to the support of a given service or content transfer. Two approaches are used in the literature: active and passive. The latter is typically more convenient, as active techniques require that the link is currently under use, beside inducing significant overhead. The existing passive solutions, however, are tailored to a specific network technology, and in some cases a sufficiently accurate estimate can be obtained only through active techniques. It follows that effective, multi-technology mechanisms for bandwidth estimation are still to be found.

Mapping the available bandwidth offered by a D2D link into the level of QoE perceived by the users is another ambitious task. Collecting traces of user throughput and corresponding QoE perceived by the user is a possible way to address this issue: data mining techniques could be applied to extract the relationship between the two factors above. There are however a number of aspects to deal with. First, while the user directly interacts with few applications, others are just running in the background, affecting the quality perceived by the user. Second, the user perception of QoE may be heavily affected by its awareness of the connection monetary cost. Third, feedback is self-reported, hence it can be inconsistent over time and over different users due to the context as well as subjective factors that are not easy to capture. It follows that innovative learning techniques are required to accurately model such a complex system, and eventually characterize the user QoE given the requested content and link properties.

Once the above information is acquired or estimated, the decision process at the user device should determine which D2D links are to be employed. Clearly, which one is the most convenient is both user- and content-dependent: either power consumption or QoE, or any combination of them, could be used. If multiple links are identified, how they should be handled represents an additional issue. Multiple connections should be established in parallel, traffic split across them and vertical handover procedures enabled whenever traffic has to be switched onto a new connection using a different technology.

VI. Conclusions

In spite of the enormous interest that they have recently received by both academia and industry, D2D communications are still far from being widely employed by users to access content and services. In this paper, we highlighted this issue and described the essential technologies that should be enabled to solve it. In particular, we argued that effective caching strategies are paramount to enabling D2D communications, and that new business models based on content trading are required to promote content caching and D2D data transfers. Additionally, whenever multiple content sources and communication links are available, the user device should be able to select the most convenient sources as well as the best way to connect with them.

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