Towards Scalable Mobile Crowdsensing Through Device-to-Device Communication

Vinícius F. S. Mota[a,*], Thiago H. Silva[b], Daniel F. Macedo[c], Yacine Ghamri-Doudane[d], José M. S. Nogueira[c]

[a]Department of Informatics – Universidade Federal do Espírito Santo, Vitória – Brazil
[b]Department of Informatics – Universidade Tecnológica Federal do Paraná, Curitiba – Brazil
[c]Computer Science Department – Universidade Federal de Minas Gerais, Belo Horizonte – Brazil
[d]Laboratoire Informatique, Image et Interaction (L3i)– Université La Rochelle, La Rochelle – France

Abstract

In mobile crowdsensing, users have a central role providing sensed data using their portable devices. Mobile crowdsensing applications have become quite popular nowadays. However, these applications can be bandwidth eager, big battery drainers, and may demand intensive network usage, which could exceed the allowance of users' mobile data plan. All these aspects may prevent users to contribute sensed data and also get valuable information from the service, which can impact the sustainability of the system. The Device-to-Device (D2D) communication paradigm arises as an approach to relieve data traffic generated by these applications, helping to let the system more sustainable. For instance, devices with a more reliable network connection can offload the network by disseminating data to other devices through D2D communication. However, mobile crowdsensing and D2D communication assume that users cooperate and allow their portable devices to be used for sensing and communication. In this work, we address the cooperation problem in the context of D2D communication to enhance mobile crowdsensing platforms. We first discuss how D2D communication can enhance mobile crowdsensing. Next, we propose and evaluate a general framework joining mobile crowdsensing and

*Corresponding author.

Email addresses: vinicius.mota@inf.ufes.br (Vinícius F. S. Mota), thiagoh@utfpr.edu.br (Thiago H. Silva), damacedo@dcc.ufmg.br (Daniel F. Macedo), yacine.ghamri@univ-lr.fr (Yacine Ghamri-Doudane), jmarcos@dcc.ufmg.br (José M. S. Nogueira)

D2D communication. This framework abstracts applications defined by the sensing platforms, it decides the communication mode – whether infrastructure or D2D – and which incentive mechanisms must be used to engage participants to cooperate. We show evidence that this new approach could lead to a more sustainable mobile crowdsensing usage.

Keywords: Device-to-Device, Opportunistic networks, Mobile data offloading.

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1. Introduction

Crowdsensing is a new sensing paradigm aiming the measurement of phenomena of common interest with the help of crowds (users). Mobile crowdsensing encompasses the notion of participatory and opportunistic sensing, where users using their portable devices are required to sense data and transmit it to services in the cloud [1]. The users' motivation for that are diverse and may include the access to valuable information generated by the service they are contributing to. Therefore, user participation is crucial in this approach of sensing and directly impacts the quality of the services that may be offered [2]. However, since mobile crowdsensing applications may consume important resources of the users' mobile devices, for instance, energy or mobile data transmission, they may deem too costly to contribute to the sensing platform.

Device-to-Device (D2D) communication is a novel wireless communication paradigm where devices communicate among them in an *ad hoc* and opportunistic fashion, which is being incorporated into the next generation of mobile Internet (5G) [3]. Since crowdsensing service providers usually assume that all participants have Internet access, one of the main advantages of using D2D communication in crowdsensing tasks is to allow participants without Internet access to contribute with and obtain valuable information from the sensing platform. Furthermore, although 5G is expected to increase the communication speed for mobile terminals, it is expected that the number of terminals, as well as the amount of data being transmitted, will grow significantly in the coming years. As a consequence, D2D also provides means to relieve data traffic from the mobile Internet Service Provider (ISP) and the crowdsensing service provider or even minimize costs for some participants of these applications, helping to make the system more sustainable. Indeed, one way to engage participants' cooperation is reducing their costs. From the users' point of view, D2D communication may decrease mobile data consumption and as well as energy consumption.

However, users still may refrain from contributing to the network even with minimal costs to do so. In fact, cooperation occurs whenever a user believes that the benefit is higher than the cost of collaborating [4]. In this case, incentive mechanisms attempt to offer benefits that outweigh the costs for each network participant. Therefore, the benefits must be clear to the users in such a way that they will let their devices be used by the sensing tasks and D2D communication processes.

This article combines the D2D communication paradigm with sensing tasks towards a sustainable cooperation model to enhance mobile crowdsensing. We first justify why D2D communication can enhance mobile crowdsensing (Section 2). Next, we discuss in which conditions users may cooperate in D2D communication (Section 3). Hence, we present a framework that enables D2D in mobile crowdsensing (Section 4). Finally, we present evidence that our proposed approach can make mobile crowdsensing more sustainable (Section 5) and present some final considerations and discussions (Section 6).

2. Device-to-Device Mobile Crowdsensing

Device-to-Device communication aims to provide ad-hoc communication between devices in close proximity for smartphones, tablets, and notebooks, with no or minimal base station intervention. D2D assumes *device relaying*, that is, devices relay packets among them [5]. The *Device-to-Device Proximity Service* specified by the 3^{rd} Generation Partnership Project (3GPP) is a standard that uses the Long Term Evolution-Advanced (LTE-A), popularly known as 4G, in the ad hoc communication (D2D inband communication). However, the term D2D communication is also used to refer to ad-hoc communication exploiting unlicensed spectrum, e.g. WiFi or Bluetooth (outband communication) [5].

In both cases, two important aspects characterize D2D communication: *i*) it is formed by devices with high storage and processing capacity, although with limited energy and usually limited bandwidth; and *ii*) the mobility follows human mobility patterns.

Mobile crowdsensing represents a class of applications that support users with sensing and computing devices to collectively contribute in a distributed process of gathering data and information extraction of common interest [1]. Thus, making feasible the monitoring different conditions of cities, as well as the collective behavior of people connected to the Internet in (almost) real-time [6]. Such a sensing process requires the active participation of people using portable devices to voluntarily share contextual information and/or make their sensed data available, i.e., the users manually determine how, when, what, and where to share the sensed data. The sensed data is sent to servers, or "sink nodes", where the data can be accessed by other participants in an aggregated fashion.

One of the most critical characteristics of mobile crowdsensing is the fact that sensing depends on the willingness of people to participate in the sensing process.

This means that users have to be always motivated to contribute. However, there are several reasons to make users unmotivated, for instance, costs of energy and network, and concerns about privacy and security. The service providers have also to be motivated to keep the services active. This means that the costs to the crowdsensing providers and ISPs have to be mitigated as well.

D2D communication by itself has the advantage of improving the spectrum usage, network coverage, and relieve data traffic from the ISP (data traffic offloading). Further, D2D communication may also improve mobile crowdsensing by providing services for devices with limited or no Internet connection. In this case, participants of the mobile crowdsensing application forward the sensed data through D2D communication. Furthermore, a set of participants may receive information through D2D whenever they are disconnected from the cloud. In this case, crowdsensing service providers also reduce their costs with data transmission.

D2D communication, thus, focuses on the offloading of communication from the mobile infrastructure towards another network (the D2D network). Another aspect of mobile crodwsensing is the locus of data processing, which can be performed on a cloud infrastructure or near the devices. Mobile Edge Computing (MEC) [7] is an area that focuses on where to perform computation considering the requirements of the applications. Note that D2D can be used in conjunction with MEC in mobile crowdsensing. While the former optimizes the network usage, the latter optimizes the use of computational resources.

Indeed, several D2D protocols have been proposed to enhance mobile networks through caching, traffic offloading, computational offloading, and content dissemination [8]. Crowdsensing differs from other mobile applications due to its characteristics of sending continuous short messages. Therefore, we considered the D2D communication as an extension of the mobile network to provide a sustainable mobile crowdsensing.

Figure 1 illustrates how traditional crowdsensing differs from D2D mobile crowdsensing. In Figure 1a, all participants have mobile Internet access, i.e. through 4G networks. Meanwhile, Figure 1b illustrates some scenarios where D2D communication enhances mobile crowdsensing, as described below:

- **Vehicular-to-Vehicular communication on the road:** Roads are likely to have weak or no mobile Internet connection. In this case, D2D communication allows sensed data sharing among drivers before sending the sensed data to the crowdsensing cloud. In this scenario, users participating in D2D mobile crowdsensing have the opportunity to receive valuable information, such as abrupt car accidents.

- **Resource sharing among crowds of users:** In scenarios with a high concentration of users participating in mobile crowdsensing, such as football

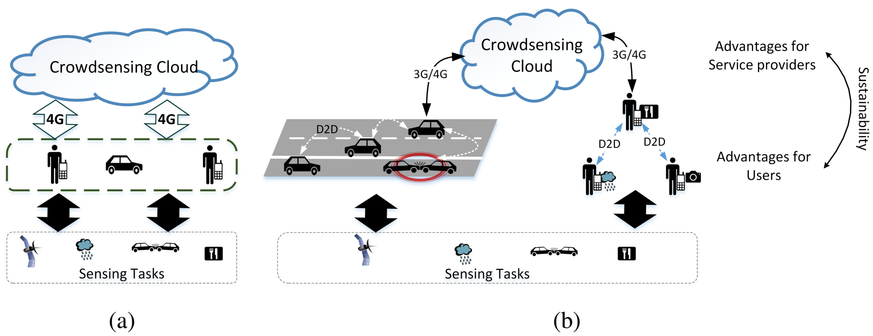

Figure 1: a) Traditional mobile crowdsensing versus b) D2D mobile crowdsensing. Cooperative users may relay data for other users using ad hoc communication.

matches or emergency situations, cellular networks may be overloaded, which can cause interruption of communication. In such situations, a group of participants using D2D communication, instead of using cellular networks, may mitigate this problem. In this case, participants of the D2D mobile crowdsensing can share information among themselves.

In a general way, D2D enhances the communication process of any mobile crowdsensing application whenever the participants have weak or no Internet access. There are several reasons that lead to the lack of Internet access through the cellular network, such as the expiration of the monthly data allowance, signaling congestion, being in a shadow region of the cellular network or even to save energy. D2D communication brings the following advantages to users, ISPs, and the crowdsensing service providers':

Mobile data offloading: D2D communication may reduce data traffic from mobile Internet providers' infrastructure, thus saving data from both customers and ISPs.

Information on the vicinity: In a mobile crowdsensing context, some devices can forward information to disconnected devices. In this way, instead of downloading information from the cloud, D2D can locally provide data for users disconnected from the infrastructure.

Spectrum usage: several mobile crowdsensing applications send continuous short messages to provide always-on connectivity, which causes signaling traffic, or so-called signaling storm [9]. In these cases, a set of devices could relay their messages through D2D communication to improve cellular network spectrum usage.

Coverage extension: Devices with no Internet could cooperate sending data through devices with better Internet access, thus, increasing the quantity of data gathered by the crowdsensing service.

Optimize bandwidth usage: Devices in the vicinity of each other usually gather almost the same information. An aggregation mechanism can reduce the amount of redundant data sent to the crowdsensing cloud.

Energy savings: Previous works demonstrated that mobile networks, such as 3G or 4G networks, drain the battery of smart devices faster than WiFi or Bluetooth [10]. Outband D2D communication allows users to exchange data through lower energy consumption networking interfaces.

Therefore, D2D communication can help mobile crowdsensing become more sustainable. However, the adoption of D2D communication by the users brings new challenges as well, such as higher delay for users that use only D2D communication and higher energy consumption for the cooperative users that relay data from the cloud to other devices. Furthermore, D2D mobile crowdsensing requires that users cooperate with the D2D communication process, as well as to the crowdsensing application.

3. Cooperation in D2D Mobile Crowdsensing

Cooperation usually occurs when an individual devotes an effort, that implies a cost in some collective activity, expecting some benefit in return [11]. In the computer network context, cooperation arises due to many reasons, for instance, technical (when users perceive service performance improvements while cooperating) and social (when cooperation brings social rewards) [4]. Cooperation in mobile crowdsensing means the active participation of each participant in sensing and transmitting data. Meanwhile, cooperation in D2D communication means the willingness of a device to relay data for others.

Participants of D2D mobile crowdsensing may present four distinct behaviors, named in this study as *Common User*, *Cooperative Sensing and Relaying*, *Cooperative Sensing*, and *D2D Eager*. Figure 2 illustrates each of these classes.

Users in the *common user* class sense and send data to the service in the cloud, as well as obtain information from it. This class represents a typical mobile crowdsensing user. The *Cooperative Sensing and Relaying* class represents users that perform all tasks of the *common user* class, and, in addition, cooperate in the D2D communication, i.e, send or receive data to or from other participants. The *Cooperative Sensing* class represents users that have no direct access to the cloud but cooperate in the sensing tasks. This class relies on participants of the *Cooperative*

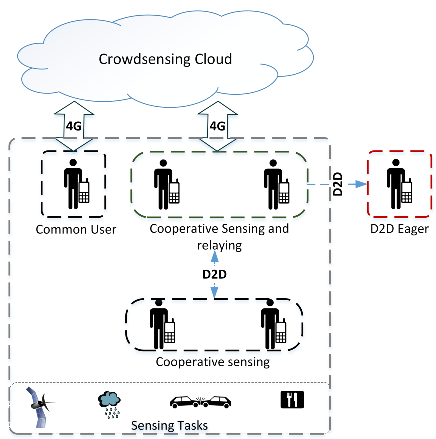

Figure 2: D2D communication jointly with mobile crowdsensing. D2D communication relies on the assumption that a set of users will cooperate and forward data to others. Mobile crowdsensing relies on the assumption that all participants gather and submit their sensed data.

Sensing and Relaying class to work properly. Finally, the *D2D eager* class represents the most selfish users, which just wish to obtain the information with the lowest cost by using D2D communication. In this last class, these participants have no cost to sense nor to forward data to the cloud.

The natural behavior of every participant of a mobile crowdsensing network is to be *non-cooperative* with the D2D network, that is, just obtaining the benefits of the sensing application. Again, cooperation arises when benefits are greater than costs. Therefore, the benefits of becoming a member of *cooperative sensing and relaying* or *cooperative sensing* must be clear to the participants. Table 1 presents the benefits and costs for each behavior group.

These benefits and costs may explain the user's participation in different classes throughout time. Let's consider a participant in the *common user* class, sensing and sending data to the cloud. When this participant loses his/her connection with the infrastructured network he/she may change to the *Cooperative Sensing* class to keep receiving and sending data. Similarly, a user may change to the *D2D eager* class and just receive new information from the cloud without having an active contribution. The *Cooperative Sensing and Relaying* class has more costs than benefits. In this case, the participant changes to this class, for example, by altruism or after receiving an incentive.

Incentive mechanisms attempt to offer benefits that outweigh costs for each

[1] In cases where opportunistic devices can access only low-speed cellular networks.

Group behavior	**benefits**	**costs**
Common User	Real-Time information	3G/4G energy consumption Data consumption Sensing energy consumption
Cooperative Sensing and Relaying	Real-Time information	WiFi energy consumption 3G/4G energy consumption Sensing energy consumption Data consumption
Cooperative Sensing	Save data consumption Save energy Improve bandwidth[1]	WiFi energy consumption Delay increase Sensing energy consumption
D2D Eager	Save data consumption Save energy Bandwidth	WiFi energy consumption Delay increase

Table 1: Benefit-cost for each class behavior in D2D mobile crowdsensing.

network participant. Several mechanisms to engage D2D relaying or sensing tasks in crowdsensing were proposed in the past years [12, 13]. In both mobile crowdsensing and D2D processes, incentives for cooperation can be *extrinsic*, in which participants receive a direct reward for participating, or *intrinsic*, in which participants must be satisfied psychologically.

With that, the next section presents a D2D mobile crowdsensing framework. This framework selects when to communicate through infrastructure network or through D2D communication, and supports incentive mechanisms that promote user cooperation.

4. A Framework for D2D Mobile Crowdsensing

4.1. Overview

D2D communication enhances mobile crowdsensing, although, brings new challenges as well. As discussed in the previous sections, the main challenge is how to motivate participants to become a relay in D2D mobile crowdsensing. This section proposes a general framework that joins D2D communication with mobile crowdsensing services.

The proposed D2D mobile crowdsensing framework is composed of three modules: sensing tasks, communication mode algorithm, and incentive mechanisms. The sensing tasks module defines what information users must collect and when they would submit the gathered information to the cloud. Note that the framework abstracts the sensing tasks, this means that it is able to handle any sort of sensing that is defined by the sensing platform. The D2D communication algorithms choose the most appropriate communication mode, that is, infrastructure-based or D2D communication. Incentive mechanisms required for both sensing application and D2D are defined in the incentive mechanism module. Figure 3 illustrates our D2D mobile crowdsensing framework.

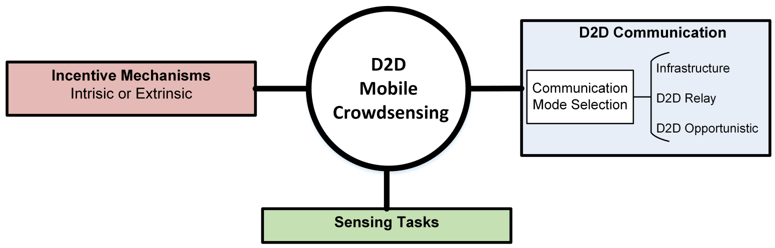

Figure 3: Framework joining sensing tasks applications and algorithms that selects the communication mode. Incentive mechanisms apply for both of them.

In previous works, we proposed an algorithm to decide which devices may cooperate using D2D communication and which devices must use the mobile infrastructure, called OppLite [14], and an incentive mechanism based on reciprocity, that is, cooperative users receive greater benefits than selfish ones, called MINEIRO - *Message-based INcentive mechanism for End-user Improvement of Routing Opportunities* [15]. In this present study, we generalize OppLite to fit mobile crowdsensing requirements and support incentive mechanisms. We propose an integration between *OppLite* and *MINEIRO* in a decentralized and centralized fashion, with minimal or no intervention on the mobile Internet infrastructure.

4.2. Choosing between infrastructure or D2D communication

OppLite is a multi-criteria decision-making framework, based on utility theory, which allows devices to switch between infrastructure and D2D communication modes based on local decisions [14]. OppLite gathers a set of properties, which can be obtained locally by the device, and maps these properties into a utility function. In this way, *OppLite* can be used without modifications in the ISP infrastructure.

The decision-making process defines one out of three communication modes in each device: in the *standard* mode, the default mode, devices communicate directly with the fixed infrastructure to request and receive content; in the *relay* mode, devices communicate directly with the infrastructure and assist devices in the *opportunistic* mode; in the *opportunistic* mode, devices communicate preferably with devices in the *relay* mode through D2D communication.

To define the communication mode, *OppLite* measures a set of properties of the mobile devices: the *Number of Neighbors*, *Battery Lifetime*, and *Link Quality*. Then, OppLite applies a sigmoid function to quantify each input. Next, the criteria are aggregated with a weighted product model to obtain a global valuation. A device switches to *relay* mode when the global valuation is greater than a user-defined relay threshold (Γ_{relay}) or switches to *opportunistic* mode if this valuation is greater than the opportunistic threshold (Γ_{opp}). Otherwise, the device resorts to the *standard* mode.

Users may define a minimum value and a weight for each criterion. For instance, a user may define that OppLite must switch its device to relay only if it has an energy level greater than 70%, more than five neighbors and high link quality. On the other hand, D2D communication typically spends less energy than fixed infrastructure communication, and more neighbors improve the chance of an opportunistic node being assisted by a relay node. Therefore, users may set OppLite to switch their devices to the D2D opportunistic mode when there is a higher number of neighbors, lower remaining battery, and weak link quality.

4.3. Engaging D2D communication

MINEIRO[2] is an incentive mechanism that engages users to forward messages to others [15]. MINEIRO is based on reciprocity, that is, users cooperate to receive cooperation whenever they need. Here, we discuss an integration between OppLite and MINEIRO to provide user-centric incentive mechanisms in a centralized and decentralized fashion, with minimal or no intervention on the ISP infrastructure.

MINEIRO builds a reputation rank based on the source of messages received by the forwarding nodes. A node increases its reputation by relaying third-party messages, while decreases it by forwarding its own messages. A node recognizes all nodes with a reputation equal to zero as selfish, and messages coming from them are rejected, with the exception of the node itself being the destination. A node forwards all messages coming from nodes with reputation greater than zero. Thus, MINEIRO provides a reciprocity-based benefit model. As a consequence, if nodes wish to increase their chances of having their messages delivered to the destination, then they should forward messages from other nodes.

Assuming that users are rational if an uncooperative behavior causes degradation in the network quality for a user, then this user tends to collaborate with the network to improve his/her network quality. Therefore, *reciprocity* is the main driving force to achieve user willingness to enable his/her device as a relay.

[2]The acronym MINEIRO is also a tribute for the people born in the state of Minas Gerais, Brazil, known by their hospitality and trust in strangers.

In crowdsensing, MINEIRO increases the reputation of devices in the *cooperative relaying and sensing* class, assisting devices in the *cooperative sensing* or *D2D eager* classes, while it decreases the reputation of devices in the last two classes.

We extend the OppLite architecture to deal with MINEIRO as an independent module, which generates inputs to the decision algorithm module. Therefore, MINEIRO assists OppLite to determine the behavior of the node.

To integrate MINEIRO with OppLite, we applied small changes in MINEIRO algorithm. Instead of increasing reputation of devices forwarding third-party messages, MINEIRO increases the reputation of a relay in every D2D communication assistance. Contrarily, MINEIRO decreases the opportunistic devices' reputation whenever OppLite forwards data for a relay. There are two ways to integrate OppLite and MINEIRO, as follows.

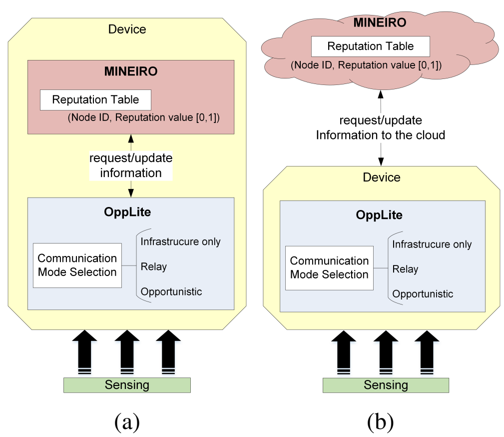

Figure 4: Distributed and centralized approaches to integrate OppLite and MINEIRO. a) OppLite and MINEIRO self contained in user device; b) MINEIRO runs on the cloud.

In the **distributed solution**, Fig. 4a, MINEIRO runs together with OppLite on the user device in order to provide information about past behavior of the encountered devices. Each MINEIRO node knows only the reputation of other nodes that interacted with it in the past. This approach requires no intervention or changes on the ISP infrastructure.

A drawback of this totally distributed solution is its scalability. In mobile networks, new nodes can appear in the network anytime, and this might make unfeasible to keep track of all nodes encountered. Furthermore, there are situations where a pair of nodes meets only once in all network lifetime, for instance, strangers that meet while moving around the city.

In the **centralized solution**, shown in Fig. 4b, MINEIRO runs on the sensing servers and it has a global view of the network. All devices receive an initial reputation. Thus, devices can be in the opportunistic mode in one day and in the relay mode in another day, and their reputation will be updated on the servers. An OppLite device in relay mode queries the reputation of an opportunistic device at the MINEIRO reputation table before assisting it. A relay informs MINEIRO, via an update message, the identification of the opportunistic device it assisted through D2D communication.

5. D2D Mobile Crowdsensing Evaluation

5.1. Scenario

We used a simulation tool to analyze how D2D communication with incentive mechanisms can enhance mobile crowdsensing applications. To achieve our goal, we developed two applications emulating mobile crowdsensing requirements:

- **D2D Extended Sensing (D2D-ES)**: This application represents devices without an Internet connection and users willing to cooperate with the sensing system, enabling to extend the network. Devices in the *cooperative sensing* class forward the sensed data to devices in the *cooperative sensing and relaying* class, as shown in Fig. 2. In their turn, devices in this last class forward the data to the crowdsensing service providers. In case the opportunistic device does not find a suitable relay device up to a tolerable delay (τ), the sensed data is sent directly to the infrastructure.

  The optimal solution for D2D-ES occurs whenever disconnected devices with sensed data in their buffer are closer to a *cooperative D2D relaying* device. In such case, sensed data from these devices are forwarded using D2D communication without a considerable delay.

- **D2D Content Dissemination (D2D-CD)**: This application models content dissemination through D2D communication. For instance, a resource sharing application where users share photos of an event among them. In such a case, D2D communication may avoid uploads and downloads of the same content several times. Devices from the *cooperative sensing and relaying* class forward received content to all other devices belonging to the *cooperative sensing* and *D2D eager* classes. Each content is forwarded up to a time-to-live defined by the parameter τ.

  In D2D-CD, a near optimal solution occurs when a minimum set of devices receive content and forward these content to a maximum number of devices through D2D communication. A near optimum solution can be modeled as the target-set problem, which is a variant of the minimum dominating-set (MDS) problem [16].

To assess our solution, we compare its results against a near optimum centralized solution with network topology knowledge, which we call Minimum Dominating-Set D2D (MDS-D2D). MDS-D2D works as follows: Assuming that ISPs have a global view of the network, they could build a graph where devices represent nodes and connections between these nodes represent edges in the graph. The MDS of the graph is calculated periodically, and isolated nodes (with degree zero) are removed from the resulting set. MDS-D2D considers all nodes in the resulting MDS as cooperative nodes.

Two extensions of the MDS-D2D algorithm, referred as MDS-D2D-ES and MDS-D2D-CD, were developed to compare the performance of D2D-ES and D2D-CD applications, respectively. In MDS-D2D-ES, nodes in the MDS remain in the *cooperative sensing and relaying* class. Nodes in the other classes attempt to forward their data through the nodes in the MDS up to a tolerable delay (τ). In MDS-D2D-CD, only nodes in the MDS request content and forward the received content to the other nodes up to a certain time-to-live.

It is important to note that these centralized solutions are hypothetical and hard in practice (if not impossible). ISPs need to define which devices are in the minimum dominating-set, therefore, the willingness of cooperation is disregarded. Furthermore, ISPs need to know the location of all devices to build the network topology, which is costly and does not scale. However, they work as benchmarks to assess our proposal.

In all applications, devices generate messages with sensed data to the mobile crowdsensing following a Weibull distribution with the shape parameter $k = 21.99$ and scale $\lambda = 1.429$ based on the frequency of check-ins in FourSquare[3] [14].

We analyze two metrics that capture advantages and disadvantages of D2D mobile crowdsensing. The first one, namely *Offloading ratio*, is calculated as:

$$\text{Offloading Ratio} = \frac{\text{number of messages transmitted through D2D}}{\text{Total of messages transmitted}}$$

The offloading ratio measures the number of messages delivered through D2D communication. This metric represents a mobile network extension in D2D-ES, while in D2D-CD it represents data consumption savings of participants and ISPs.

[3]Foursquare is a popular location-based system where users publish their GPS positions (check-ins).

The second metric is *D2D Delay*, since the delay to find a suitable D2D relay in the network represents the major disadvantage of using D2D communication. The delay is calculated only for the messages delivered using D2D communication.

5.2. Simulation Setup

OppLite, MINEIRO and mobile crowdsensing applications were developed in the ONE simulator [17]. The evaluation employed the Rollernet dataset available in Crawdad [18]. We used three hours of 62 volunteers carrying iMotes at the Pari-Rollerskating tour in 2016. This trace logs every Bluetooth device in range, and it has 1112 devices in total. This trace illustrates a crowd situation scenario, which represents the best case scenario for D2D mobile crowdsensing.

We evaluate the performance by varying the relay threshold (Γ_{relay}) and the opportunistic threshold (Γ_{opp}) parameters according to the following values:

$$\Gamma_{relay} = [0, 0.2, 0.5, 0.7]$$
$$\Gamma_{opp} = [0.01, 0.2, 0.5, 0.7]$$

As mentioned previously, Γ_{relay} represents a threshold in OppLite and MINEIRO so that the device switches to relay mode and participates in *D2D relaying*. Meanwhile, Γ_{opp} defines when devices use only D2D communication instead of infrastructure. Smaller values of these thresholds mean that users are more cooperative, while bigger values make it harder for devices to switch to D2D mode. The set of criteria parameters in OppLite is listed in Table 2. These values are based on previous analysis of *OppLite* [14], representing that devices with higher battery and more than three neighbors are more likely to cooperate.

Table 2: OppLite criteria values.

Criterion	**Center**	**Weight**
Neighbors	3	0.4
Battery Level	70	0.5
Link Quality	15	0.1

The delay tolerance (τ) of the D2D-ES and MDS-D2D-ES applications were set to 1200 seconds, which means that a device in D2D mode waits up to 20 minutes to find a relay. After that, OppLite returns the device to infrastructure mode. In the D2D-CD and MDS-D2D-CD applications, τ was set to 600 seconds, which means that devices in the *cooperative sensing and relaying* group forward content to devices in the *cooperative sensing* or *D2D eager* groups up to 10 minutes. We run each simulation scenario 15 times and show the results with 95% confidence intervals.

The MDS-D2D algorithm was implemented in Python and uses as input the same mobility trace and message creation pattern as the simulations. The MDS-D2D calculates the minimum dominating-set every 60 seconds.

5.3. Results

In the D2D-ES application, devices with no Internet connection attempt to find cooperative devices in the network to forward the sensed data through D2D communication. As a consequence, such devices save data consumption from their data allowance albeit attending a delay until finding a device in the relay mode.

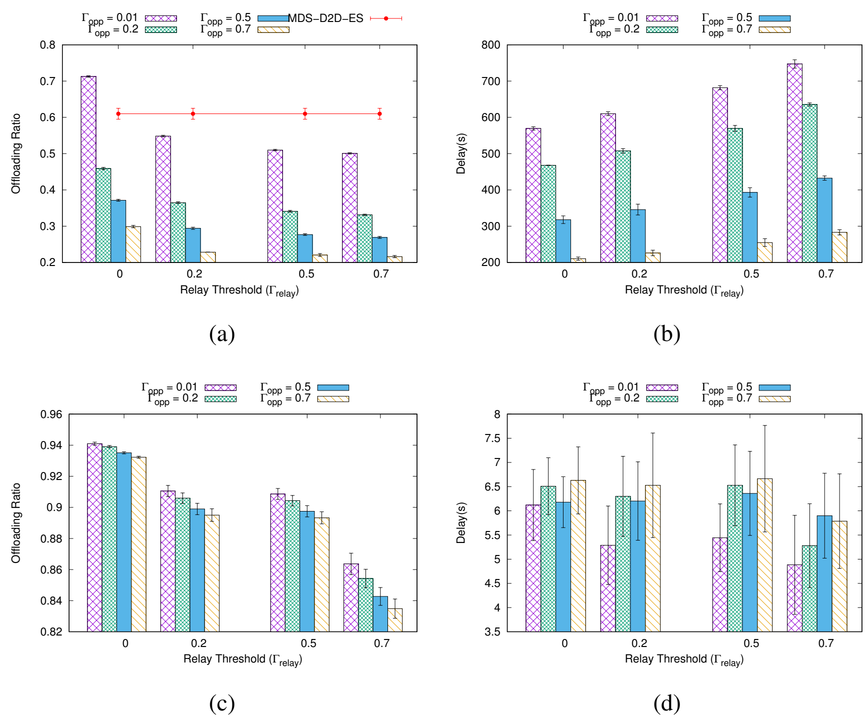

Figure 5: The advantage and impact of content dissemination through D2D communication. a) D2D-ES: Offloading ratio; b) D2D-ES: Delay until finding a suitable relayer; c) D2D-CD: Offloading ratio; d) D2D-CD: Delay until finding devices willing to receive content through D2D.

Figure 5 depicts how user willingness and OppLite communication decision methods affect these advantages and disadvantages. Figure 5a shows how much data was sent through D2D communication, thus saving data consumption from D2D cooperative sensing users. In the best case, when all users are cooperative, 70% of the data traffic can be sent through D2D relay devices. Increasing the relay threshold decreases the number of devices acting as D2D relays, and reduces the offloading ratio in 21% on average. However, these results show that larger values of Γ_{opp} increase the resistance of users switch their devices to D2D mode, reducing 35% of the offloading ratio on average.

Meanwhile, the centralized version, MDS-D2D-ES, offloads 60% of the messages on average. Furthermore, due to the characteristics of the mobility trace, on average, 23 nodes belong to the MDS during the simulated time and each cluster has 3 nodes, causing this high offloading ratio. Note that, our solution are able to provide good results when compared to this near-optimum MDS-D2D-ES strategy.

The main disadvantage for mobile crowdsensing participants using only D2D communication is the delay incurred to find a cooperative D2D relay. As shown in Figure 5b, increasing the relay threshold also increases the delay in D2D mode to find a suitable relay. Increasing Γ_{opp} decreases the delay due to fewer devices in opportunistic mode.

In the near-optimum MDS-D2D-ES strategy, almost all nodes have connections with at least one node in the MDS. In such case, the time to find a relay was on average 9.74 seconds with standard deviation equal to 17.13 seconds. One might question why the delay is not constant and low. The reason for that is because some nodes are isolated. For instance, some nodes take up to 26 seconds to find a node belonging to the MDS in our scenario. This lower delay represents an advantage for the centralized solution. However, nodes in the minimum dominating-set are forced to cooperate, condition hard to be achieved successfully in practice.

In the D2D content dissemination (D2D-CD) application, devices in the D2D cooperative class, which are connected to the cloud and contribute to the D2D network, forward all content received from the cloud to devices in D2D mode. Figure 5c shows the offloading ratio for all thresholds analyzed. In this application, up to 94% of the messages were sent through D2D communication when all networking participants agree to use D2D mode. The offloading ratio decreases with the increase of Γ_{relay} because the number of devices disseminating content decreases as well. This also explains why the delay increases with Γ_{relay}, as shown in Figure 5d. Devices in D2D mode disseminate content to all devices in the D2D opportunistic mode in their vicinity, which causes lower delays.

On the other hand, the centralized version, MDS-D2D-CD, achieves 99.9% of messages transmitted through D2D communication[4]. D2D-CD offloads only 5% less than centralized version when nodes are cooperative. When increasing the

[4]We omitted MDS-D2D-CD results in the Figure 5c for the sake of clarity.

restriction of nodes to cooperate (Γ_{relay} and Γ_{opp}) D2D-CD offloads 19% less data than MDS-D2D-CD. However, this higher offloading ratio of the centralized MDS-D2D-CD occurs due to the higher number of nodes in the MDS, whom are forced to cooperate and forward data.

Our results show that centralized solutions can achieve higher offloading ratio but do not take into account the user willingness to cooperate with the network. Our distributed proposals overcome this issue by letting users parametrize their level of cooperation, providing a high offloading ratio. However, these distributed solutions introduce delays in the communication process.

6. Final Considerations

This article demonstrated how Device-to-Device communication makes mobile crowdsensing more sustainable by making it less dependent on infrastructure networks, such as 3G or 4G networks. D2D communication explores the network interfaces of smart devices to provide communication in an *ad hoc* fashion. Mobile crowdsensing integrated with D2D communication, what we call D2D mobile crowdsensing, may extend the coverage of the sensed area by providing services to users with no or limited Internet access. However, it imposes constraints as well, such as resource consumption from cooperative users.

Thus, this article proposed a Device-to-Device mobile crowdsensing framework. In order to do so, the framework is built on the concept of incentive mechanisms. A multi-criteria decision algorithm decides between D2D or infrastructure communication mode and a reputation-based incentive mechanism engages users' cooperation.

Simulation results showed that there is a tradeoff that defines the participants' behavior: Participants using D2D communication save data and energy consumption, however, they must tolerate a certain delay. Cooperative users improve their reputation value and increase their chances of using D2D communication in the future.

There are several open challenges in D2D mobile crowdsensing not addressed in this article, such as privacy and security. Sensed data transmitted through D2D communication may impose threats to privacy. For instance, this data could be used to infer the users' personal behavior and preferences, such as commonly visited locations, lifestyle, and health condition. Therefore, it is mandatory to prevent leakage of private information of individuals, while transmitting data through unknown third-party devices. The framework here presented is a good starting point to help face such challenges.

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