Beyond Opportunistic Networking Protocols: a Disruption-Tolerant Application Suite for Disconnected MANETs

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ABSTRACT

Delay/disruption-tolerant networking and opportunistic networking have emerged as promising solutions to support communication between people in environments devoid of any infrastructure network. Although many protocols have been proposed in the literature to support message forwarding or message dissemination in such conditions, a very few of these protocols have been implemented in fully-functional communication systems, and can thus be used to conduct experiments with real applications and real users. In this paper we present an application suite we designed in order to provide people with opportunistic communication means such as email, text and voice messaging, file sharing, etc. We also present some results of a preliminary experimentation campaign we conducted in order to evaluate these applications in a real setting.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Store and forward networks*

General Terms

Design, Experimentation

Keywords

delay/disruption-tolerant networking, opportunistic computing

1. INTRODUCTION

In a mobile ad hoc network (MANET), mobile hosts can communicate directly with one another using direct pair-wise wireless links. Because it requires no fixed infrastructure –and most of the time no explicit administration– a MANET can prove extremely useful to support communication in challenging situations, such as in rural, remote, or disaster-struck areas.

In the literature MANETs are often assumed to be fully connected networks: messages can thus be forwarded at any time from host to host in the network, using one of the many dynamic routing protocols that have been developed specifically for that purpose during the last two decades [13]. Unfortunately the assumption that a MANET is necessarily a connected network is somewhat contrived: many real MANETs are, at best, only partially or intermittently connected.

A MANET can for example become disconnected when the mobile hosts that compose this network are sparsely or irregularly distributed. The whole network then appears as a collection of distinct, continuously changing "islands" –or connected components– rather than as a single, connected network. In such conditions the mobility of hosts can be considered as an advantage, as it makes it possible to bridge the gap between non-connected parts of the network, using mobile hosts as carriers –or *data mules*– that can carry messages over long distances. A message can thus be stored temporarily on a host while this host is moving in the network, and be forwarded later to another host when circumstances permit. This *"store, carry, and forward"* approach fits in the general category of disruption-tolerant –or delay-tolerant– networking (DTN [2]): connectivity disruptions are indeed tolerated thanks to the mobility of hosts, but this approach generally yields long transmission delays because transporting a message from source to destination can take a long time when one or several data mules are involved during the transport. The term *opportunistic networking* has been proposed in [17] to denote delay/disruption-tolerant networking when radio contacts between mobile hosts are not planned in advance and must thus be exploited opportunistically. This is typically the case in many kinds of disconnected MANETs (or D-MANETs), where the mobility pattern of each host is actually that of its physical carrier. If the physical carriers are for example human beings carrying laptops or smartphones, then radio contacts cannot always be predicted, although each contact is still an opportunity for two hosts to exchange messages.

Many papers published in the last few years address the problem of supporting communication in D-MANETs (good surveys can notably be found in [17] and [19]). An overwhelming majority of the protocols described in these papers have been implemented and evaluated only in network simulators. Of course network simulators can prove very useful. They make it possible to play the same scenario many times, which is quite convenient when several protocols must be compared in similar conditions. They also make it possible to verify the scalability of a protocol, while conducting experiments with hundreds or thousands of mobile devices could be a tedious –and expensive– task. Yet it is our conviction that protocols must also be implemented and tested for real, so as to avoid some simplifications and not to neglect some constraints that would render these protocols ineffective in real conditions.

For example, due to the limitations of some simulators, many authors run simulations in which battery-powered handheld devices such as laptops, netbooks, or smartphones are assumed to be always on, and therefore always available to exchange messages with any other neighbor device. In real life, though, experience shows that users generally prefer to preserve the battery of their devices, which are thus switched off –or put in suspend mode– most of the time, and are only switched on for short durations. Simulation scenarios in which battery-powered handheld devices are assumed to be always on are thus overly optimistic.

Another typical example is that simulators are often used to evaluate how messages can propagate in a D-MANET, but not how distributed applications could perform in such a network. Yet since a D-MANET is a network in which transmission delays can be very long and where transmissions can even fail altogether, legacy applications (most of which are TCP-based) could not run in such conditions. Indeed, designing and implementing distributed applications capable of running in a D-MANET is quite a challenge. The peer-to-peer model should obviously be preferred over the client-server model, because as a general rule no host can be considered as stable and accessible enough to play the role of a server for all other hosts. Additionally, any distributed application running in a D-MANET must obviously be able to tolerate long transmission delays, and occasional transmission failures as well. Legacy applications must therefore be re-examined based on these premises, and new applications have to be designed accordingly.

In the remainder of this paper we present a suite of applications we designed along that line, together with lessons learned from the first experimentation campaign we conducted in order to evaluate how these applications can perform –and be accepted by users– in real-life conditions. Our application suite relies on a communication middleware system we designed and implemented. This communication system is only described briefly in Section 2, but interested readers can find details in [5]. In Section 3 we present the applications we proposed to users during the experimentation campaign. This campaign is described in Section 4, together with some of the results obtained on that occasion. In Section 6, which concludes this paper, we describe our plans for future work.

2. OVERVIEW OF DODWAN

Building an application suite for D-MANETs requires some communication middleware system with which mobile hosts can collaborate in a peer-to-peer manner to ensure message transportation. DoDWAN *(Document Dissemination in mobile Wireless Ad hoc Networks)* is a communication middleware system we designed along this line. DoDWAN, whose general architecture is presented in Figure 1, is distributed under the terms of the GNU General Public License[1].

DoDWAN has been designed so as to be configurable, extensible and customizable. Thanks to the available documentation, API and tutorial, one can easily develop new DoDWAN-based applications and deploy them on different types of devices such as laptops or Android smartphones. DoDWAN has originally been implemented

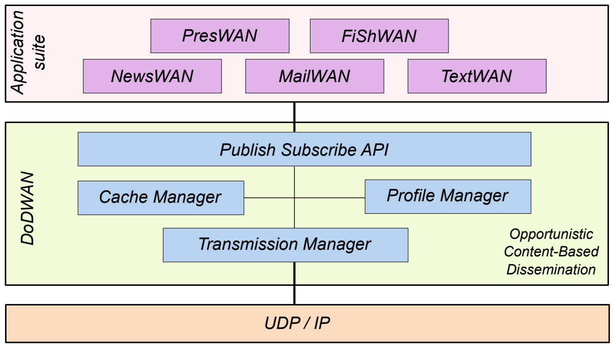

Figure 1: Architecture of the DoDWAN system

so as to rely on Wi-Fi interfaces running in ad hoc mode, and this is the way it is usually used in most situations (including the experiments reported in this paper). Yet it has also been experimented in a military tactical network, using VHF battlefield radios with built-in modems instead of Wi-Fi interfaces, and proved very robust and reliable in such harsh conditions [6]. Additionally, DoDWAN is provided with a set of tools that are useful for trials, such as a communication logger, a neighborhood logger, an administration console, etc.

DoDWAN supports content-based information dissemination in D-MANETs. This is a characteristic it shares with the Haggle system, while the DTN2 system is rather meant to support destination-driven message forwarding.

In content-based networking, information flows towards interested receivers rather than towards specifically set destinations. This approach notably fits the needs of applications and services dedicated to information sharing or event distribution. It can also be used for destination-driven message forwarding, though, considering that destination-driven forwarding is simply a particular case of content-driven forwarding where the only significant parameter for message processing is the identifier of the destination host (or user).

DoDWAN implements a selective version of the epidemic routing model proposed in [18]. It provides application services with a publish/subscribe API. When a message is published on a host, it is simply put in the local cache maintained on this host. Afterwards each radio contact with another host is an opportunity for the DoDWAN system to transfer a copy of the message to that host.

In order to receive messages an application service must subscribe with DoDWAN and provide a *selection pattern* that characterizes the kind of messages it would like to receive. The selection patterns specified by all local application services running on the same host define this host's *interest profile*. DoDWAN uses this profile to determine which messages should be exchanged whenever a radio contact is established between two hosts.

Our approach while developing DoDWAN has been quite pragmatic: rather than designing a clever and complicated protocol that can only run efficiently in very specific conditions, we deliberately designed a quite simple protocol that performs satisfactorily in most situations. As a general rule, a mobile host that defines a specific interest profile is expected to serve as a mobile carrier for all messages that match this profile. Yet a host can also be configured so as to serve as an altruistic carrier for messages that present no interest to the application services it runs locally. This behavior is optional, though, and it must be enabled explicitly by setting DoDWAN's configuration parameters accordingly. Details about this interaction scheme and about how it performs in real conditions can be found in [5].

Mobile hosts running DoDWAN only interact by exchanging

[1]http://www-irisa.univ-ubs.fr/CASA/DoDWAN

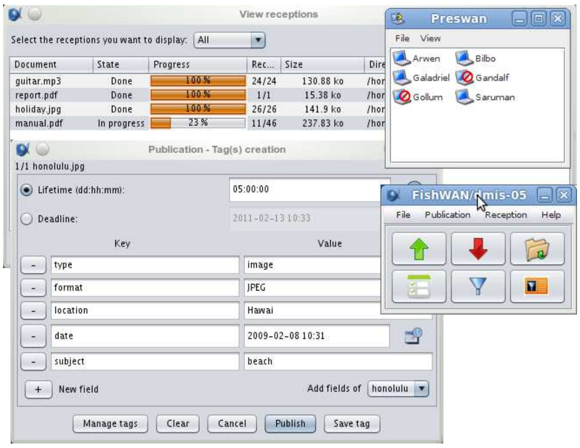

Figure 2: Screenshots of some DoDWAN applications

control and data messages encapsulated in UDP datagrams, which can themselves be transported either in IPv4 or IPv6 packets. Large messages are segmented so that each fragment can fit in a single UDP datagram. Fragments of a large message can propagate independently in the network and be reassembled only on destination hosts.

3. APPLICATION SUITE

A suite of applications suitable for disconnected MANETs has been developed on top of the DoDWAN middleware system.

Some of these applications are strongly inspired from legacy Internet communication services: electronic messaging, discussion service, and instant messaging. Since such services rely on the client/server paradigm, each host running DoDWAN must also run pseudo-servers that implement the POP3, SMTP, NNTP and IRC protocols. These pseudo-servers communicate with each other through the DoDWAN middleware system in a peer-to-peer mode. End-users can use the standard client programs they are already familiar with (for example Thunderbird or XChat IRC) in order to access their email accounts, newsgroups or IRC channels.

Other applications have been specifically designed for the DoDWAN middleware system, with specific user interfaces. One of these applications makes it possible to visualize the user's direct neighbors. A peer-to-peer filesharing application that allows users to define their interests for particular files and to receive them according to their content. Finally, simple text and voice messaging applications are available. These are well adapted to small devices such as smartphones, for they only require limited user interaction.

Figure 2 shows screenshots of some of these applications. In the remainder of this section, we detail how some of these applications make use of DoDWAN's content-based information dissemination to implement application-level communication schemes.

NewsWAN.

NewsWAN (News distribution in Wireless Ad hoc Networks) is a discussion service that is strongly inspired from the legacy Usenet service created in the 1980s. NewsWAN implements an NNTP pseudo-server running on each device. The *Thunderbird* agent is used as a standard user interface.

Newsgroups, representing topical categories, are used as content description for message dissemination. Any user can create a newsgroup, or discover existing ones. When an article is published to a particular newsgroup, a message is put in the cache maintained by DoDWAN, with the newsgroup as content description. The message then starts propagating from device to device in the network, being carried by those devices whose users have subscribed to the newsgroup considered. Symmetrically, whenever the DoDWAN middleware obtains from a peer host an article that matches its own "interest profile"—that is, an article that pertains to a newsgroup it has been ordered to maintain locally—this article is simply put in the local cache, and the NewsWAN program is notified of this reception, so the article can be made available for the user's newsreader.

FiShWAN.

FiShWAN (File Sharing in Wireless Ad hoc Networks) is a peer-to-peer filesharing application, which can be compared with popular filesharing applications such as Emule or Kaaza. FiShWAN leverages on DoDWAN's content-based communication model, and provides users with facilities to describe the content of the files they want to publish or to obtain, and to easily store and retrieve these descriptions when needed. File descriptors are directly used by DoDWAN while performing selective message dissemination.

MailWAN.

MailWAN (Mail exchange in Wireless Ad hoc Networks) is an email exchange service that allows users of mobile devices to send and receive email. It implements POP3 and SMTP pseudo-servers running on each mobile device, accessed locally by standard email agents such as Thunderbird. MailWAN is implemented using the publish/subscribe programming interface offered by DoDWAN.

In the Internet email forwarding relies on an address-based scheme. In contrast DoDWAN implements a content-based propagation model. When publishing an email message, MailWAN includes the email address of the recipient as the content description of the message. In order to receive messages it also registers with DoDWAN as a subscriber for messages whose content description is the email address of the local user.

All mobile devices do not necessarily have to serve as carriers for all email messages. The domain part in an email address is considered as the identifier of a community of users. Thus members of a community collaborate to disseminate messages addressed to any member of this community. Through the usual tool in her email agent, the user can create an account (with a dedicated domain name) for each of the communities she belongs to.

TextWAN and VoiceWAN.

TextWAN and VoiceWAN are text and voice messaging services inspired from the well-known SMS service, and extended to non-textual messages. Each user can belong to one or several groups, and messages can be sent either to specific users or to groups of users. Messages are forwarded towards their destination(s) by disseminating through all devices that belong to the same groups as the target(s).

4. EXPERIMENTATION

DoDWAN and the application suite described in Section 3 are meant to be useful in challenged environments, especially when traditional communication services are not available. Yet before trying to use DoDWAN and its applications in really harsh conditions, we conducted a preliminary experimentation campaign inmon a more "cozy" environment. This campaign involved groups of volunteer students (up to 25 volunteers during each trial), that were equipped with DoDWAN-enabled netbooks and were strongly invited to use DoDWAN and its applications during and between classes, but also out of the campus (at home, during week-end trips, etc.). Several trials were conducted during that campaign, with durations ranging between a couple of weeks and 6 months.

The netbooks were Dell Inspiron Mini 9 and Mini 10, running an Ubuntu/Linux system. The Wi-Fi interface on each netbook was configured to operate by default in ad hoc mode, using an SSID dedicated to the experiment. The users were not allowed to switch this interface to managed mode, thus preventing wireless connections to access points that may be present in their environment. However, they had the possibility to access the Internet sporadically using the builtin Ethernet interface, while wireless communication was reserved for opportunistic communication with DoDWAN.

All the software needed for the experiments had been packaged in two Debian packages to ease its deployment. These packages included not only DoDWAN and its applications, but also a number of administration tools. Among these tools was a network configurator that could control the Wi-Fi and Ethernet interfaces, and a power manager. This power manager could detect the starts and shutdowns of the netbooks, as well as suspend-to-ram and resume events, and notify DoDWAN of these events. Such events are important for the DoDWAN system, as it uses them to update its perception of a host's neighborhood, and to adapt its gossiping with neighbors accordingly. Another administration tool allowed software upgrade via an Internet connection established through the Ethernet interface. Because of the rather long duration of the whole campaign, bug corrections or parameter adjustments had to be applied during the course of the experiment. Users were informed of these changes (typically via articles published in a dedicated newsgroup accessible with the NewsWAN application), and were invited to temporarily connect their netbook to the Internet, so that an automatic upgrade of the software could be performed. Another administration tool was used to automatically upload the different traces collected on a mobile host to a server in our laboratory. This upload occurred whenever the host's Ethernet interface was plugged. The storage capacity on each netbook was actually sufficient to store the entire trace of a trial. It was however interesting for us to collect traces dynamically, as it allowed us to detect and correct software issues as early as possible.

The execution traces collected on each netbook during the whole campaign pertained to the activity of the operating system, of the DoDWAN middleware, and of the DoDWAN-based applications. The analysis of these traces allowed us not only to check the behavior of DoDWAN's protocol, but also to get a better understanding of the behavior of the users. During the whole experimentation campaign we collected 935 Mbytes of trace data, corresponding to about 8.7 million elementary events observed on the netbooks. In the remainder of this section we illustrate the kind of information that can be extracted from these trace data.

Figure 3 depicts the volatility of 20 netbooks (carried by as many volunteer students) during a 2-month trial, represented as an up/down line for each netbook. The figure clearly shows that the activity of the 20 netbooks varied a lot during the trial, with a global activity level remaining rather low. The right part of Figure 3 focuses on the afternoon of the 4th day of the trial. It can be observed that only 6 netbooks out of 20 had a significant period of activity (longer than one hour) during that afternoon. Very short periods of activity were observed, for example on netbooks *n3* and *n14* whose traces show activity periods of less than a minute. It turns out that several users sometimes opened the lid of their netbook for a few seconds, just to have a glance at the clock widget or to "check their messages". Ironically, these users were anxious to preserve the battery level of their netbook but, by doing so, they did not allow the local DoDWAN system to interact effectively with neighbor hosts,

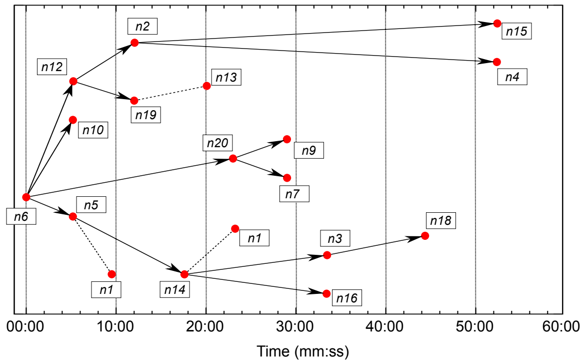

Figure 5: Timeline of the dissemination of a message

thus diminishing the interest of having DoDWAN-based applications running on their netbook. Indeed, this observation alone bears out that experimentation in real conditions can highlight technical and non-technical issues that simulators can hardly pinpoint. In that particular case, it notably confirms that the volatility of battery-powered devices must not be underestimated when designing protocols and applications for opportunistic computing.

Figure 4 depicts the evolution of the neighborhood of a typical netbook (namely netbook *n14*) during the same 2-month trial. The neighborhood of a netbook is here defined as the number of other netbooks that are within the radio range of this netbook at a given time. In the figure it can be observed that the number of neighbors of netbook *n14* varied continuously and unexpectedly during the 2-month trial. Interestingly, the neighborhood of each netbook was rarely greater than 10 and no clear pattern can be observed in its evolution, although the 20 students often attended the same classes in the same rooms. This confirms that neighborhood between hand-held mobile hosts is the result of user-driven volatility and mobility, which when combined together make it hardly predictable. Opportunistic networking and computing then take all their sense, as they allow messages to flow between devices, even though these devices are almost never active at the same time.

The trace data collected during the campaign also allowed us to check the message dissemination scheme implemented in DoDWAN. Figure 5 shows the dissemination of a particular message, which was published by netbook *n6* during one of the trials. This message was actually an article published by *n6*'s user in a particular newsgroup. The dissemination of the message is here displayed as a tree. Indeed this tree was somehow built opportunistically by the DoDWAN protocol, as radio contacts between netbooks occurred over time. The delay-tolerant nature of the dissemination scheme appears clearly in this example: after the message was published on *n6* at time 00:00, *n6* met *n5*, *n10* and *n12* about 6 minutes later. Since the message matched the interest profiles of these three netbooks they all got a copy of the message, and thus became carriers of this message. *n5* later met netbook *n1*, but since the message did not match the interest profile of *n1* it did not become a carrier (this is expressed by the dotted line in the figure). *n5* went on to meet *n14*, which got a copy of the message and itself later passed this message to *n3* and *n16*. After 53 minutes, 12 netbooks had received the message, and 3 additional netbooks had been proposed this message but had denied it.

Globally, the experimentation campaign revealed a utilization ratio of the DoDWAN applications lower than what we had expected. For example, the two-month trial discussed above totalized 419 messages published with MailWAN, NewsWAN and FiShWAN,

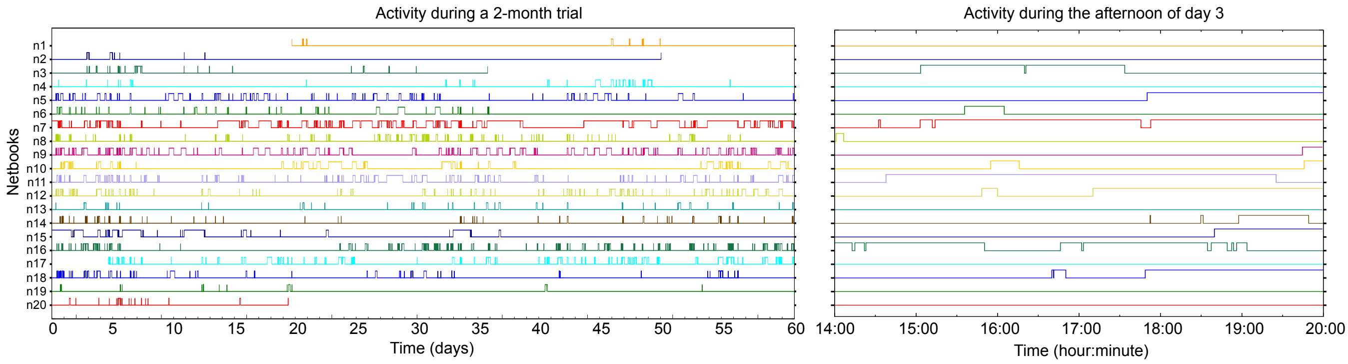

Figure 3: Activity of 20 netbooks during a 2-month trial

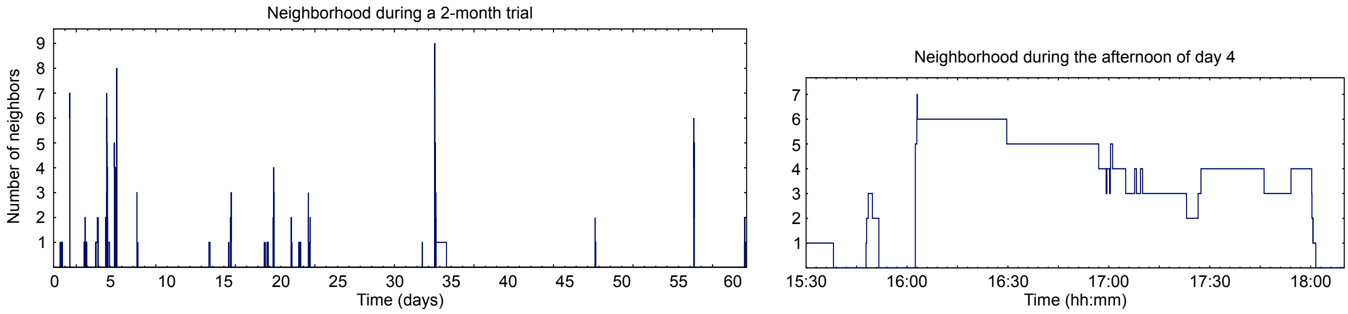

Figure 4: Evolution of the neighborhood of netbook n14 during the 2-month trial

with relative parts of respectively 38%, 43% and 19%. This is partly due to the fact that our volunteer students did not rely entirely on the DoDWAN applications, as they evolved in an environment where traditional communication means (such as 3G infrastructure and Wi-Fi hotspots) were widely available. Indeed, interviews with users showed that they often felt reluctant to rely on asynchronous communication tools, as they are addicted to quasi-interactive communication (even email is often expected to be transmitted almost instantaneously). This fact should be taken into consideration when preparing to run DTN experimental trials, and selecting applications for these trials. The killer-application is still to be found with this respect.

5. RELATED WORK

As mentioned in Section 1 only a few protocols for D-MANETs have been implemented in fully-functional communication systems, which are now openly distributed and are thus accessible to developers. Among these systems are the DTN2 system [1], the Haggle system [8], and our own system DoDWAN [5].

Such systems make it possible for developers to design distributed applications, and to use these applications to evaluate the potential of delay/disruption-tolerant and opportunistic networking in challenged environments.

Many possible applications for D-MANETs have been discussed in the literature, although not so many have been implemented and tested in real settings. Email can typically be implemented in a delay/disruption-tolerant environment, due to its inherently asynchronous nature. [15] thus describes a DTN-enabled Email service based on a modification of the SMTP protocol. This service, which involves static kiosks and mobile data mules, has notably been tested during a limited field deployment in rural India.

DTN applications inspired from Twitter [9], Facebook [11] and Podcasting [14] have also been proposed recently. [4] proposes to use DTN communication in a Finnish chromium mine. A series of experimental trials have been carried out between 2008 and 2010, in different countries, as part of the EU-funded Networking for Communications Challenged Communities (N4C) project. Trials conducted in Swedish Lapland for example focused on how Web and Email applications based on the PRoPHET protocol [12] and on the DTN2 system [3] could meet the needs of reindeer herders.

The idea of using smartphones as DTN-enabled voice-messaging devices has been addressed in many papers [16, 7, 10]. A trial deployment was notably carried out in Uganda. Results of this trial are discussed in [7].

Most of the above-mentioned papers propose to implement applications based on the DTN2 system, although some of them define their own protocol to support applications. Haggle and DoDWAN yet differ from DTN2 in that they support opportunistic content-driven information dissemination, while DTN2 primarily supports destination-driven message forwarding. Opportunistic content-driven dissemination presents a number of advantages in a D-MANET, for messages can be published in the network with no specific destination. Each mobile host can thus decide to accept –and thus become a carrier for– a message based on its own interest profile or, if needed, based on its willingness to serve as a benevolent carrier for this message. This approach can bring significant benefits in a D-MANET, especially when mobility and contact patterns cannot be predicted.

To the best of our knowledge no extensive experimental trial has ever been conducted with the Haggle system in a challenged environment. As explained in Section 4 the DoDWAN system and the associated applications have so far only been tested in a campus environment (although DoDWAN itself has already proved effective for military tactical communication). The results obtained from this preliminary trial however suggest that DoDWAN and the application suite are reliable enough, so our next goal will be to deploy a small flotilla of DoDWAN-based netbooks and smartphones in a rural environment.

6. CONCLUSION

In this paper we have presented an application suite we designed and implemented in order to provide users with communication facilities in challenged environments, such as in rural, remote, or disaster-struck areas. The mobile devices used in such conditions are assumed to constitute a disconnected mobile ad hoc network (D-MANET). An opportunistic, content-driven communication model is used to enable message forwarding in such conditions, using mobile hosts as carriers that allow messages to propagate network-wide. This model is implemented in DoDWAN, a communication system we designed and which is distributed under the LGPL license.

Our DoDWAN-based application suite has first been implemented on netbooks, and tested during a preliminary experimentation campaign involving about 20 volunteers per trial. This campaign has confirmed that the communication model is effective at disseminating messages in a flotilla of mobile hosts, and has allowed us to learn a number of lessons from the observations made on that occasion.

Work is now in progress to deploy the same applications on Android-based smartphones. A trade-off must here be made between preserving the limited power budget of the device and ensuring sufficiently frequent radio contacts with other devices. The latter objective is a tricky one since, unlike netbooks, smartphones tend to enter suspend-mode whenever they are not used interactively.

The portability and extended autonomy of smartphones (compared to netbooks) are expected to open up a wide range of field experiments. In the near future we plan to conduct experimentation campaigns, combining this time netbooks and smartphones, in environments devoid of any communication infrastructure.

Acknowledgments

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