Computer Communications 48 (2014) 5–19

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Protocols, mobility models and tools in opportunistic networks: A survey

Vinícius F.S. Mota [a,b,*], Felipe D. Cunha [a], Daniel F. Macedo [a], José M.S. Nogueira [a], Antonio A.F. Loureiro [a]

[a] Computer Science Department, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil
[b] Computer Science Laboratory (LIGM), Université Paris-Est, Champs sur Marne, France

ARTICLE INFO

Article history:
Available online 27 March 2014

Keywords:
Opportunistic networks
Delay-tolerant networks
Context-awareness
Vehicular ad hoc networks
Pocket switched networks

ABSTRACT

In opportunistic networks, instead of assuming an end-to-end path as in the traditional Internet model, messages are exchanged opportunistically when an encounter happens between two nodes. In the last years, several forwarding algorithms to efficiently decide when to forward messages were proposed. Those protocols are commonly suitable to a specific scenario, which has led to the creation of new subtypes of networks. Two different examples are *pocket switched networks* – PSN and *vehicular networks* – VANETs, since those networks have different features like a specific mobility pattern and intermittent connectivity. In this article we present an overview of opportunistic networks, proposing a taxonomy which encompasses those new types of network. We discuss the commonly used tools, simulators, contact traces, mobility models and applications available. Moreover, we analyzed a set of forwarding protocols to map the approach used by the research community to evaluate their proposals in terms of mobility, contacts and traffic pattern, reliability of simulations and practical projects. We show that although researchers are making efforts to use more realistic contact models (e.g., using real traces) the traffic pattern is generally disregarded, using assumptions that may not fit real applications.

1. Introduction

The Internet has brought new applications such as email, World Wide Web and VoIP, revolutionizing the way we access and create information. In the last years, smartphones, tablets and other mobile communication devices have become popular. These devices have significantly increased their storage capacities, processing and specially their communication technologies, ranging from Bluetooth and Wi-Fi to 4G. This communication capacity enables novel classes of applications, ranging from mobile social networks to safety control in vehicular networks. Those applications sometimes are based on the direct communication among the devices, which forward messages from one device to another. Such mobile networks where data is forwarded opportunistically whenever a "contact" takes place are known in the literature as opportunistic networks [1]. The mobility in this kind of network is crucial, since it helps to spread data more efficiently. However, such mobility is considered a challenge because it may cause scattering of nodes, preventing the correct data delivery [2].

Networks formed by mobile devices carried by people (a subset of opportunistic networks) are called Pocket Switch Networks (PSNs) [3]. Two important aspects characterize the PSNs: (i) they are formed by devices with high storage and processing capacity, however with limited energy and usually limited bandwidth; and (ii) their movement is influenced by human mobility. Vehicles equipped with processing capability and wireless communication devices are another application of opportunistic networks. Vehicles send and receive information to other vehicles as well as to a roadside infrastructure, providing valuable information for intelligent traffic systems, as well as improving the driver's security and route decision. vehicular networks (VANETs) do not have energy constraints, however VANETs suffer from high mobility and variable node density, which can influence the communication among nodes [4,5]. Finally, *Inter-Planetary Networks* (IPNs) are networks established to ensure communication among Earth and satellites or even other planets [6]. Due to the movement of planets and satellites as well as their rotation, the communication exhibits frequent interruptions. Also, the significant distances among planets cause the communication to exhibit long delays.

* Corresponding author at: Computer Science Department, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil. Tel.: +55 31 3409 5860; fax: +55 31 3409 5858.

E-mail addresses: vfsmota@dcc.ufmg.br (V.F.S. Mota), fdcunha@dcc.ufmg.br (F.D. Cunha), damacedo@dcc.ufmg.br (D.F. Macedo), jmarcos@dcc.ufmg.br (J.M.S. Nogueira), loureiro@dcc.ufmg.br (A.A.F. Loureiro).

http://dx.doi.org/10.1016/j.comcom.2014.03.019
0140-3664/

The research in opportunistic networking started in the context of interplanetary networks, where the Delay/Disruption Tolerant Network (DTN) concept was born [6]. In our view, DTNs are a special case of a much larger class of networks, called opportunistic networks (or OppNets). OppNets are networks where the low node density and/or unpredictability of node movement, together with the harsh nature of the wireless links, may create long periods of node disconnections as well as partitions among sections of the network. Many studies about OppNets were published in the literature in the last ten years. Among those, message routing, mobility characterization and the impact of the mobility model on the performance of the network are the most frequent topics.

In the literature, there are several surveys addressing different aspects of OppNets [7–12]. Grasic and Lindgren [12] analyzed the evaluation practices in the literature, taking into account factors such as the mobility and connectivity models, network traffic, node characteristics and code validation, and repeatability. Other surveys are limited to a description of existing protocols as well as the research challenges in the field [7–11]. This article does not provide an in-depth and exhaustive review of research proposals in the area. Instead, the focus of this article is to show the evolution of OppNet research and evaluation, providing the readers a comprehensive step-by-step survey of the protocols and discussing the simulators, platforms and tools available for researchers. While Grasic and Lindgren's survey only analyzed network simulators, we provide an overview of platforms, testbeds and applications as well, and also propose a taxonomy of the different platforms and mobility models.

This article surveys the evolution of the opportunistic networking research and describes the state-of-the-art in evaluation practices in the field. First, we propose a taxonomy of the different types and applications of opportunistic network. Next, we analyze a set of forwarding protocols and classify them according to the taxonomy. Then, we describe the existing mobility models, contact traces, tools and simulators public available. Moreover, we discuss the evaluation practices and the common assumptions made by the research community to evaluate their proposals and the practical issues for the feasibility of opportunistic networking.

The rest of this work is organized as follows: Section 2 presents an overview of OppNets. Section 3 presents the main projects, deployments and classes of applications found in opportunistic networks. Section 4 presents a taxonomy to classify the forwarding protocols designed for stochastic, social or context aware networks. Section 5 surveys and analyzes the existing mobility models and traces, followed by an enumeration of the simulators and tools in Section 6. Section 7 discusses the main challenges in OppNets. Finally, Section 8 presents the concluding remarks.

2. Opportunistic networking

Opportunistic networks are networks that, unlike classic networks, are prone to frequent disconnections and high communication delays. The frequent disconnections preclude the use of classic message forwarding paradigms, since those are based on the establishment of an instantaneous end-to-end path from source to destination. As a consequence, OppNets employ the *store-carry-forward* paradigm, where messages are stored in intermediate nodes until a suitable forwarding opportunity occurs. In some scenarios, it may be the case that node disconnection is the most frequent state, and as such the node may only communicate when a link is established (in OppNet jargon, this is called a *contact*). The node, then, selects a set of messages to be forwarded using the recently established link, using some sort of priority scheme [7]. The process of storing a message for later transmission is also known in the literature as *custody*. The second key aspect of OppNets is the typically long end-to-end delay. In interplanetary networks, this delay is due to the distance among source and destination, while in vehicular networks or pocket switched networks this is due to the long disconnection times. As a consequence, OppNet messages tend to be *self-contained*, as connection-oriented protocols or interactive protocols tend to perform poorly under long delays (due to the high bandwidth-delay problem [13]).

Since OppNets were proposed after DTNs, it is important to clarify the difference between both concepts, which are frequently mistaken as the same thing. DTNs were developed for the interconnection of networks (i.e., an inter-network protocol for Internets), where the interconnection among those networks suffers from long disconnections and interruptions. DTNs operate over the TCP/IP protocol stack, serving as a "gateway" for interconnecting Internets over delay and disruption-constrained links. OppNets, meanwhile, are a broader concept, since they support the disconnection and interruption of communication among Internets, as well as among nodes within the same network. OppNets do not mandate the use of the TCP/IP protocol stack, and are characterized by the use of the *store-carry-forward* paradigm, where messages are stored in secondary storage devices (e.g., hard drives and flash cards), and those messages are forwarded whenever a communication link is established (a *contact*). Although the protocols proposed in the DTN RFCs may be employed in other scenarios (e.g., VANETs or PSNs), it may be too costly on others (e.g., sensor nodes installed in wild animals [14]), and as such only the concept of custody and self-contained messages is kept.

2.1. Types of opportunistic networks

Due to the frequent confusion among the DTN and OppNet concepts, as well as the large range of applications and restrictions found in OppNets, we propose a taxonomy to clarify the similarities and differences among the concepts and applications. OppNets are also found in the literature under different names, such as challenged networks or intermittently connected networks, referring to scenarios in which it is not possible to guarantee an end-to-end path between nodes. The proposed classification is shown in Fig. 1. Opportunistic networks are divided into challenged networks and delay tolerant networks, which are detailed below.

2.1.1. Delay tolerant networks

We classify DTNs as the scenarios that strictly follow the Bundle Protocol implementation [15]. This protocol's development is led by the IRTF DTN Research Group [16], which is the core of DTN research. Fig. 2 shows the protocol stack of a DTN node. The Bundle implements the *store-carry-forwarding* paradigm, implementing hop-by-hop reliability and security, instead of end-to-end as in the TCP/IP protocol stack. The bundle protocol handles intermittent connectivity (storing a message) and carrying this message until a contact takes place. In this moment, the routing protocol will decide if the node will forward or not the stored messages. The DTN2 reference implementation is based on the Linux operating system and follows the standards described in the RFC 4838. This implementation also supports the *Licklider Transmission Protocol* (LTP) [17], used for reliable communication among two DTN gateways. Two classes of networks belong to DTNs:

- *Underwater Networks:* Enable applications for oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance. Underwater communication presents several challenges [8,18]: almost all underwater communication uses *acoustic waves*, since radio waves suffer severe attenuation in salty water; the medium access is an open problem in underwater networks; nodes are expensive and the monitoring areas are