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Energy-aware opportunistic mobile data offloading under full and limited cooperation

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A B S T R A C T

Opportunistic networking (a.k.a. device-to-device communication) is considered a feasible means for offloading mobile data traffic. Since mobile nodes are battery-powered, opportunistic networks must be expected to satisfy the user demand without greatly affecting battery lifetime. To address this requirement, this work introduces *progressive selfishness*, an adaptive and scalable energy-aware algorithm for opportunistic networks used in the context of mobile data offloading. The paper evaluates the performance of progressive selfishness in terms of *both* application throughput and energy consumption via extensive trace-driven simulations of realistic pedestrian behavior. The evaluation considers two modes of nodal cooperation: full and limited, with respect to the percentage of nodes in the system that adopt progressive selfishness. The paper demonstrates that under full cooperation the proposed algorithm is robust against the distributions of node density and initial content availability. The results show that in certain scenarios progressive selfishness achieves up to 85% energy savings during opportunistic downloads while sacrificing less than 1% in application throughput. Furthermore, the study demonstrates that in terms of total energy consumption (by both cellular and opportunistic downloads) in dense environments the performance of progressive selfishness is comparable to downloading contents directly from a mobile network. Finally, the paper shows that progressive selfishness is robust against the presence of non-cooperative nodes in the system, and that in certain scenarios the system-level performance does not deteriorate significantly under limited cooperation even when 50% of the nodes in the system do not adhere to the specifics of the algorithm.

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1. Introduction

Due to the proliferation of mobile devices in recent years, mobile network operators are now expected to satisfy immense data traffic demands via the cellular network (i.e. more than 24 exabytes of monthly mobile data traffic by 2019 as predicted by Cisco [1]). Thus, mobile data offloading has been suggested as a complement. One promising approach for offloading network traffic is based on mobile opportunistic networks which allow contents to be shared directly among mobile devices when in proximity.

Previous studies on mobile data offloading via opportunistic communication [2–4] aim at maximizing the data delivered to mobile devices. However, they do not consider the limited battery capacity of the mobile device. The energy consumption is strongly affected by the 802.11 radio interface when turned on in ad-hoc mode [5].

Recent studies propose duty cycling as a viable strategy for decreasing energy consumption in opportunistic networks [6,7]. Such solutions however assume that all nodes participating in the content exchange are altruistic and willing to share data with others throughout their lifetime. This may be an overly optimistic assumption, and nodes that have already obtained all contents of interest may prefer to opt out of distribution in order to save energy. By default, selfishness has always been considered harmful to the performance of opportunistic networks and different mechanisms have been suggested for providing incentives for nodes to behave altruistically [8], as well as for detection and avoidance of selfish nodes throughout the routing process [9]. However, they do not take into account the price in terms of energy consumption that a node pays for being altruistic.

In this work we aim at decreasing the energy consumption while *at the same time* retaining the application throughput of an opportunistic network. The work is motivated by our previous study [10] in which we argue that opportunistic mobile data

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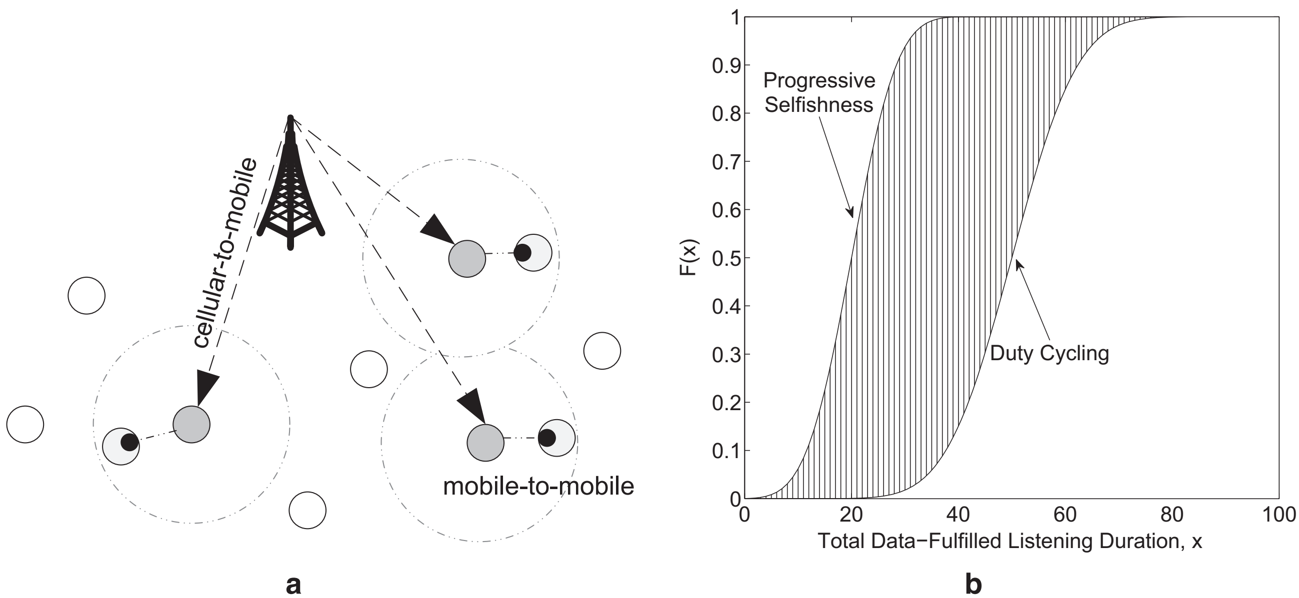

Fig. 1. (a) Mobile data offloading: only a subset of nodes in the observed area download contents directly from the cellular network; the rest of the nodes obtain contents opportunistically. (b) Cumulative density function of the lower and upper bounds of the total listening duration achieved by progressive selfishness.

offloading should take into account not only the requirements of mobile operators, but also those of mobile devices. The main contributions are:

- We revisit the concept of selfishness in opportunistic networks and demonstrate that in contrast to prior understanding, selfishness can decrease energy consumption while satisfying user demands.
- We propose an adaptive and scalable energy-aware algorithm for opportunistic networks, *progressive selfishness*, which combines the merits of two energy saving mechanisms that have always been considered mutually exclusive: duty cycling and selfishness.
- We perform extensive trace-driven simulation analysis using realistic pedestrian mobility and evaluate the performance of progressive selfishness under two modes of nodal cooperation: full and limited, with respect to the percentage of nodes in the system that adopt the algorithm.
- We show that under full cooperation progressive selfishness is robust against parameters such as node density and initial content availability. The results demonstrate that progressive selfishness can achieve up to 85% energy savings while losing as little as 1% in application throughput.
- We show that under limited cooperation progressive selfishness is robust against the presence of non-cooperative nodes in the system. We also show that in sparsely populated areas deviating from the progressive selfishness algorithm deteriorates the performance of cooperative and non-cooperative nodes alike.

The rest of this paper is structured as follows. Section 2 revisits popular energy saving mechanisms, and introduces progressive selfishness. Section 3 outlines the evaluation scenario, and Sections 4 and 5 present results from realistic pedestrian mobility scenarios under full and limited cooperation, respectively. In the context of our findings, Section 6 discusses previous work. Finally, Section 7 concludes the study.

2. Progressive selfishness

We assume that users are pedestrians equipped with mobile devices moving in an urban area, e.g. a grid of streets in a city, and that a mobile operator wishes to disseminate data to all users in the observed area, software updates or special offers, for instance. However, downloading data separately to every user may result in high traffic volumes traversing the operator's network. To relieve the cellular infrastructure, the mobile operator relies on data offloading as illustrated in Fig. 1(a). Upon entering the area, some users get parts of the data pushed from the cellular network directly into their caches; these nodes serve to bootstrap the offloading process. The rest of the users attempt to download content items opportunistically when in communication range with a node that already has the data. In this work we do not consider how the mobile operator determines the best candidate nodes to initially carry contents. Instead we focus on the performance of the opportunistic data dissemination.

Throughout its lifetime a node is either data-seeking, or data-fulfilled. A node is *data-seeking* if it is missing one or more content items of those provided in the observed area. A node is *data-fulfilled* if it already has downloaded all content items.

In the context of mobile data offloading, the main objective of a data-seeking node is to obtain as many content items of those provided by a mobile operator as possible. However, a data-seeking node needs to discover data at a low energy cost. In order to save energy while searching for contents, we allow data-seeking nodes to duty cycle (DC) within a cycling interval T_c, i.e. to iteratively turn their radio interfaces on and off. A node can only discover other peers and exchange data with them while its radio interface is turned on. In our previous work [6] we suggest that the time during which a radio interface is turned on should be chosen uniformly at random $d \sim \mathcal{U}(0, T_c)$ in the beginning of every cycling interval, and the radio interface should be consecutively turned off for the remaining $(T_c - d)$ time units. We adopt this strategy, since it was shown to decrease energy consumption roughly by half without incurring significant application throughput losses for an opportunistic content distribution system.

Once a node obtains all content items of interest, its objective changes and the focus shifts from downloading data to saving energy. Ultimately, a node would save greatest amount of energy if it chooses to opt out of the data dissemination process at the moment it becomes data-fulfilled. We refer to such behavior as *strict selfishness*. However, if all data-fulfilled nodes choose to be strictly

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