The Virtue of Selfishness: Device Perspective on Mobile Data Offloading

Sylvia T. Kouyoumdjieva and Gunnar Karlsson
School of Electrical Engineering and ACCESS Linnaeus Center
KTH Royal Institute of Technology, Stockholm, Sweden
Email: {stkou, gk}@ee.kth.se

***Abstract*—Direct device-to-device communication based on the 'store-carry-forward' paradigm is considered a feasible means for offloading mobile data traffic. Employing device-to-device communication however should satisfy user demand without greatly affecting battery lifetime. In order to provide satisfactory application throughput it is often assumed that nodes behave altruistic, and are willing to share contents for an infinite amount of time. In the context of energy savings, this assumption is overly optimistic. This work evaluates the performance of a publish/subscribe opportunistic content dissemination application that uses duty cycling for energy saving *and* allows nodes to behave in a selfish manner. Two types of selfishness are introduced: strict and mild. The paper presents the impact of selfishness on both application throughput and energy consumption via extensive trace-driven simulations, and demonstrates that introducing strictly selfish behavior on top of duty cycling leads to great decrease in energy consumption (up to 90% in certain cases) without causing significant loss in application throughput. Moreover, when the duration of the mild selfishness interval is chosen appropriately, mild selfishness can lead to even further decrease in energy consumption while at the same time increasing the application throughput.**

***Index Terms*—device-to-device communication, selfishness, duty cycling, mobile data offloading**

I. Introduction

Direct device-to-device communication (D2D) based on the 'store-carry-forward' paradigm (often referred to as opportunistic communication) has been considered a suitable mechanism for offloading mobile data traffic due to the abundance of contact opportunities in urban areas with users on-the-go. Opportunistic mobile data offloading has been extensively studied [1], [2], [3] with the objective of minimizing traffic volumes in operators' networks. This objective however should not be considered in isolation. Instead, the requirements of mobile devices as participants in the data offloading process should also be taken into consideration. Although current smartphones are powerful, a major constraint continues to be the limited battery capacity. Thus, for devices to be willing to participate in mobile data offloading, the energy cost incurred by direct D2D communication should be minimal.

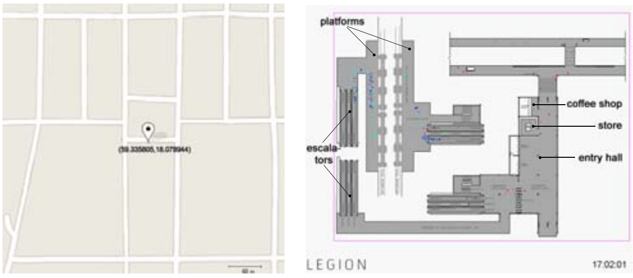
There have been efforts towards minimizing the battery consumption in wireless mobile networks without infrastructure with the most prominent example being duty cycling which has been widely explored in sensor [4], [5], delay tolerant [6], [7], and recently also opportunistic networks [8]. These solutions have been proven to significantly reduce the energy consumption, however they assume that all nodes participating in the content exchange are altruistic, and willing to share data with others throughout their lifetime. We see this assumption as being overly optimistic, and believe that nodes may exhibit different levels of selfishness, especially since direct D2D communication is not the only means for obtaining data in the context of mobile data offloading.

The main contribution of this work is to *simultaneously* evaluate the energy consumption and application throughput (i.e. goodput) of a D2D content dissemination application which adopts two energy saving techniques: *duty cycling* and *selfishness*. We perform extensive trace-driven simulation analysis using realistic pedestrian mobility which is not tractable for mathematical analysis, and demonstrate that combining selfishness and duty cycling decreases energy consumption in mobile devices participating in opportunistic mobile data offloading up to 90% without significantly affecting goodput. To the best of our knowledge, this work is the first to consider the effects of *both* duty cycling and selfishness on the performance of D2D communication in the context of mobile data offloading.

II. Evaluation Scenario

We assume that users are pedestrians equipped with mobile devices moving in an urban area, e.g. a grid of streets or a subway station, and that a mobile operator wishes to disseminate some data (i.e. transport information or software update) to users entering the area. Instead of downloading data separately to every user, the mobile operator relies on data offloading. Upon entering the area, some users download *parts* of the data directly from the cellular network, and store them in their caches. The rest of the users attempt to download content items opportunistically when in communication range with a carrier of data. Note that nodes are interested in obtaining all content items, regardless of the data carrier that provides them; in other words, the system is content-centric. Observe also that in this work we do not argue how the mobile operator determines the best candidate nodes to initially carry contents.

Since the focus of this work is mainly in the domain of D2D communication, we here briefly present a sample publish/subscribe service provided by an opportunistic content distribution system [9] which allows nodes to discover contents in other peers. We assume that nodes are subscribed to feeds (i.e. topics) of interest, and each feed may hold



(a) (b)

Fig. 1. The urban scenarios: (a) a part of downtown Stockholm, Östermalm, and (b) a two-level subway station.

one or more entries. Both feeds and entries are announced by the mobile operator to nodes entering the observed area. Whenever the radio interface of a node is turned on, the node periodically broadcasts beacons to inform potential neighbors about its presence. (In the current study, the beaconing period is set to $T_b = 0.5$ s.) When a device encounters another node (the communication range is assumed to be 10 m), it checks in a local cache whether this is the first time it meets the node or, if not, whether the node has obtained new contents since their last contact. If so, the device initiates a request-response communication and at each step it tries to match the remote feeds/entries with its local subscriptions until it finally downloads content items of interest.

For the evaluation in this work we use an implementation of the opportunistic content distribution system for the OMNeT++ simulator [10].

A. Mobility scenarios

In order to realistically recreate pedestrian mobility, we use Legion Studio[1], a commercial multi-agent simulator initially developed for designing and dimensioning large-scale spaces via simulation of pedestrian behaviors. Legion Studio allows the use of open systems, where entities can enter and leave the system according to a predefined pattern. Each simulation run results in a mobility trace file, containing a snapshot of the positions of all nodes in the system every 0.6 s.[2]

We consider two evaluation scenarios: an outdoor urban scenario, modeling the Östermalm area of central Stockholm, and an indoor scenario, recreating a two-level subway station (Fig. 1).

The urban outdoor scenario (which we further refer to as the Östermalm scenario) consists of a grid of interconnected streets. Fourteen passages connect the area to the outside world. The active area of the outdoor scenario is 5872 m^2. Throughout their lifetime nodes are constantly moving in the area.

The indoor scenario defines a subway station with train platforms connected via escalators to the entry-level. Nodes can arrive on foot from any of the five entry points, or when a train arrives at the platform. The train arrivals contribute to a burstiness in the node arrivals and departures. Nodes congregate while waiting for a train to arrive, or while taking a break in the store or the coffee shop at the entry level. The active area of the scenario is 1921 m^2.

If not stated otherwise, we have chosen the input parameters of the Östermalm and the Subway scenario such that they result in approximately the same mean node density of 0.1 nodes/m^2. (More information can be found in [11].)

B. Content initialization

In our evaluation scenarios we assume that all nodes carry devices, however not all nodes are interested in the contents provided by the mobile operator in the observed area. Instead, only a portion p of them participate in the D2D content exchange. Whether a node participates in the content exchange is determined randomly upon its entry in the area. If not stated otherwise, we assume that the operator wishes to disseminate data to interested nodes of approximately 100 kB which is announced on a single feed (e.g. textual traffic updates). The data is then divided into 10 entries, each of mean size of 10 kB, and a standard deviation of 2 kB; we note that due to mobility, entries of size 10 kB allow for utilization of short contact opportunities among nodes. Upon entrance in the observed area the cache of each participating device is initially populated with 5 randomly chosen entries; thus, throughout its lifetime in the simulation each participating node strives to obtain the rest of the entries provided by the mobile operator.

We note that the amount of data initially injected into the cache of participating devices is an engineering parameter, and depends on the node density in the area, as well as the overall size of the information the operator is willing to disseminate to subscribers. Detailed evaluation of this dependency however falls out of the scope of the current study. Furthermore, initial content carriers may also represent nodes that arrive with contents in the area.

C. Performance metrics and configurations

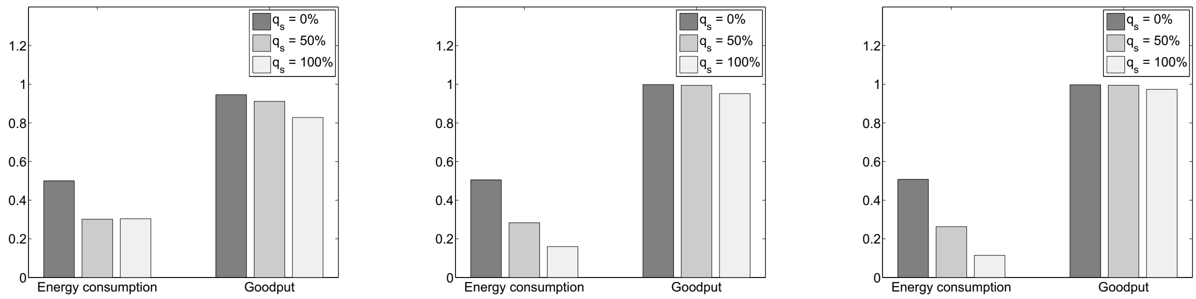
We focus on two performance metrics: *energy consumption* and *goodput* (i.e. application throughput) from a system perspective. Since we study an open system, it is important that the metrics are normalized with respect to the nodes' sojourn time in the simulation. The system goodput is simply the sum of the number of bytes downloaded B_i by each node divided by the sum of the lifetimes of nodes in the simulation t_i, or $G = \sum B_i / \sum t_i$. We only count bytes of fully downloaded content items (entries), so the goodput is a measure of the system usefulness for the users, i.e. how much content it can provide. The energy consumption of the system is defined as the sum of the energy consumed by the radio interface, normalized with respect to the sum of nodes' sojourn times. Thus, the energy consumption can be expressed as $E = \sum E_i / \sum t_i$.

We compare the performance of the following two configurations with respect to the above performance metrics:

- ***ON*** — a system in which the radio interface is always turned on, and no energy saving mechanism is applied.

[1]Legion Studio is available at http://www.legion.com/.

[2]Traces are available at http://crawdad.org/kth/walkers/.



(a) (b) (c)

Fig. 2. Normalized energy consumption and normalized goodput under strict selfishness for the Östermalm scenario when (a) 10%, (b) 50% and (c) 100% of the nodes entering the area are subscribed to the same feed.

- ***DC*** — a system in which duty cycling is applied as an energy saving strategy. Each node chooses uniformly at random the duration of its listening interval for every cycle throughout its lifetime; when not in use, the radio is completely suspended [8]. Since nodes do not have knowledge about their environment, e.g. when another peer would enter in communication range or whether peers in range carry content items of interest, assuming uniform distribution of listening durations is appropriate. All nodes adhere to the same cycling interval. For the purpose of this study, the cycling interval is set to 10 s.

For both configurations we consider IEEE 802.11b in ad-hoc mode as wireless technology to support D2D communication.

III. Results

We define two types of selfishness: strict and mild. A node is *strictly selfish* if it turns off its radio interface immediately after it has obtained all items announced by the mobile operator. A node is *mildly selfish* if after obtaining all items of interest it is still willing to contribute to the content dissemination process for a limited amount of time before turning off its radio interface. In the following subsections we first assume all nodes to be strictly selfish, and we then release this assumption.

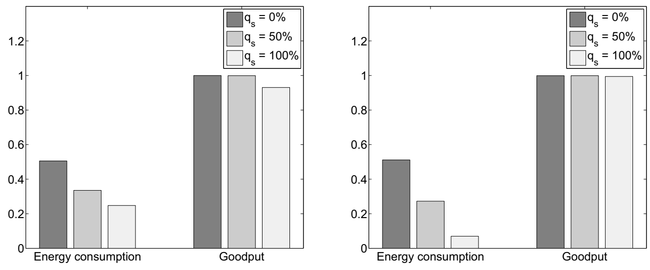
A. Strict selfishness

Fig. 2 and 3 illustrate the effects of strict selfishness on the energy consumption and goodput for the Östermalm and Subway scenario, respectively, when nodes duty cycle. For each scenario we show results for three different values of the participation rate p, as well as three different levels of selfishness q_s. While the participation rate is a measure of the popularity of a feed, the level of selfishness relates to the percentage of nodes that behave strictly selfish in the network. q_s = 0% means that all nodes in the network are altruistic, and no selfishness is applied; q_s = 100% means that all nodes are strictly selfish. All results in Fig. 2 and 3 are normalized with respect to the energy consumption and goodput of an ON configuration with given participation rate.

First we discuss the results for the Östermalm scenario (Fig. 2). We note that over all participation rates p duty cycling decreases by half the energy consumption as compared to the ON case (refer to the bars corresponding to q_s = 0%) without harming significantly the goodput of the system (the system suffers at most 5% goodput loss at p = 10%, and as little as 0.3% goodput loss at p = 100%). Introducing strict selfishness reduces the energy consumption across all participation rates, and across all levels of selfishness. Not surprisingly, this reduction comes at a price in goodput, and this price is higher when the participation rate is lower. We note that at low participation rate, Fig.2(a), increasing the level of selfishness from 50% to 100% does not introduce further energy savings. Although nodes turn off their radios once they have obtained all content items of interest, due to the low content popularity, nodes spend on average the same time searching for content items as they do when only 50% of the nodes are strictly selfish. As the participation rate increases, Fig. 2(c), the energy consumption is reduced to approximately 10% of the energy consumed by an ON configuration, and this reduction comes at a price of less than 3% of goodput loss.

Fig. 3 presents the results for the Subway scenario. (Results for p = 50% are not shown due to space constraints.) Although the Subway scenario has the same node density as the Östermalm scenario, the energy savings are higher across all participation rates p, and they come at a lower goodput price. This is due to the different mobility patterns in the two scenarios, as well as the space in which mobility occurs. (The Subway scenario exhibits longer physical contact durations due to the congregation of nodes at platforms, as well as the burstiness of arrivals [11].)

Finally, let us briefly discuss these results from the perspective of mobile operators. In the context of mobile data offloading, the loss in goodput in both the Östermalm and the Subway scenario implies that the missing data would be downloaded directly from the cellular network instead. However, we see that the additional load on the operator's network is minimal (at most 5%) in comparison to the energy savings in mobile devices (up to 90%). This observation hints that in contrast to previous studies [1], [2], [3] mobile data



(a) (b)

Fig. 3. Normalized energy consumption and normalized goodput under strict selfishness for the Subway scenario when (a) 10%, and (b) 100% of the nodes entering the area are subscribed to the same feed.

offloading should not be considered only from the viewpoint of operators but should instead treat the requirements of mobile nodes with equal significance.

B. *A word about strictly selfish always-on nodes*

A question worth investigating is whether duty cycling is really needed for decreasing the energy consumption, or whether it would suffice to apply strict selfishness to a system in which all nodes are always listening? Table I presents a comparison of the performance of ON and DC under strict selfishness with q_s = 100% for the Östermalm scenario. Observe that all data is normalized with respect to the energy consumption and goodput achieved by an altruistic ON configuration with the respective participation rate p. (We do not show the results for the Subway scenario, however we remark that the performance is similar.)

TABLE I
PERFORMANCE OF ON AND DC UNDER STRICT SELFISHNESS WITH q_s = 100% FOR THE ÖSTERMALM SCENARIO WITH PARTICIPATION RATE p.

Configuration	Energy	Goodput
ON, p = 10%	56.3%	86.2%
DC, p = 10%	30.4%	82.8%
ON, p = 50%	29.9%	95.7%
DC, p = 50%	16.0%	95.2%
ON, p = 100%	20.8%	98.3%
DC, p = 100%	11.5%	97.4%

Although over all participation rates p, strict selfishness in ON yields higher goodput in comparison to DC, the improvement is marginal (less than 4% for p = 10%). This marginal goodput improvement comes at a cost of as much as 26% more energy (for p = 10%) in the case of ON. As the participation rate increases, strict selfishness in ON significantly reduces the energy consumption (to 20% for p = 100%). Duty cycling however yields higher energy savings while providing similar levels of content dissemination.

C. *A word about initial content downloads*

Another question is whether the initial content distribution plays a significant role in the dissemination process. Naturally, under equal node density conditions the higher the number of content items initially downloaded to a node's cache, the higher the energy savings, and the higher the goodput. We note that if content items are initially sparsely distributed (either due to low density, or low initial content distribution), epidemic dissemination of contents continues to take place. However some or all of the node may not experience selfishness. For nodes that do not experience selfishness, the energy savings will be due solely to duty cycling, i.e. approximately 50% of the energy of ON. Table II shows how many nodes do not experience selfishness throughout their lifetime under different amount of initial content downloads, and different participation rates for the Östermalm and Subway scenario. For each scenario we perform 3 simulation runs, and for each run we select randomly the initial content carriers. Again, the difference in performance of the Östermalm and Subway scenarios is due to the mobility patterns in the observed area. Thus, mobile data offloading via direct D2D communication should take into account the mobility of nodes in the area with respect to the physical structure of the area.

TABLE II
PERCENTAGE OF NODES THAT DO NOT EXPERIENCE SELFISHNESS FOR THE ÖSTERMALM AND SUBWAY SCENARIO WITH $q_s = 100\%$, PARTICIPATION RATE p AND DIFFERENT AMOUNT OF INITIAL CONTENTS.

Configuration	Initial downloaded contents			
	1	3	5	7
Östermalm, p = 10%	100%	63.6%	48.6%	44.1%
Östermalm, p = 100%	100%	11.7%	7.5%	5.5%
Subway, p = 10%	100%	35.1%	24.9%	15.6%
Subway, p = 100%	100%	2.8%	1.4%	1.1%

TABLE III
GOODPUT (GP) AND ENERGY CONSUMPTION (EN) FOR THE ÖSTERMALM SCENARIO WITH $q_s = 100\%$, PARTICIPATION RATE p AND DIFFERENT CONTENT SIZES.

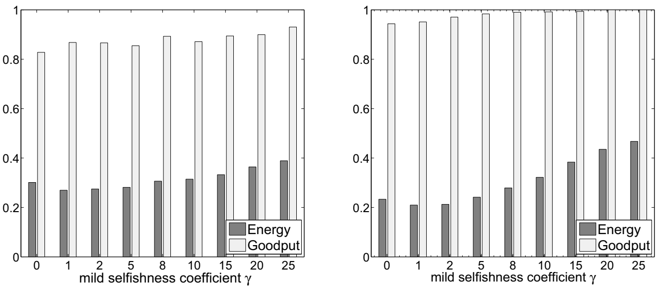
Configuration	Initial content size					
	100 kB		1 MB		10 MB	
	Gp	En	Gp	En	Gp	En
DC, p = 10%	90.5%	29.8%	92.8%	37.2%	79.6%	50.4%
DC, p = 100%	98.7%	11.4%	98.9%	17.3%	91.7%	42.2%

D. *A word about initial content sizes*

Until now we assumed that the operator wishes to disseminate information of a rather small size. Table III shows the system performance for offloading contents of size 1 MB and 10 MB for the Östermalm scenario. (Results for the Subway scenario are omitted.) The cache of each participating node is initially populated with half of the data. All results are normalized with respect to the goodput and energy consumption of an altruistic ON configuration. We see that across all content sizes and all participation rates, combining duty cycling with selfishness allows nodes to offload significant amounts of mobile data via direct D2D communication at a lower energy cost.

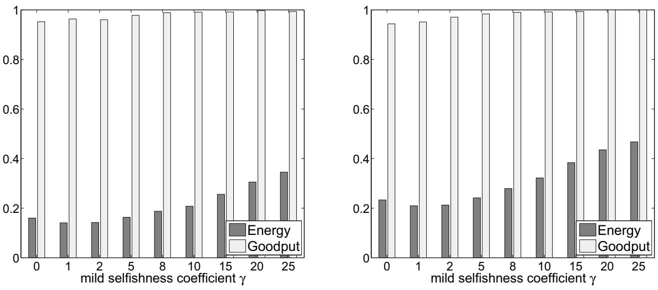
E. *Mild selfishness*

When nodes are mildly selfish, they are willing to share contents with other subscribers for some limited amount of time after they have obtained all items of interest. We here



(a) (b)

Fig. 4. System performance under mild selfishness for the (a) Östermalm and (b) Subway scenario when the participation rate p = 10%; dark bars represent energy consumption, light bars represent goodput.



(a) (b)

Fig. 5. System performance under mild selfishness for the (a) Östermalm and (b) Subway scenario when the participation rate p = 50%; dark bars represent energy consumption, light bars represent goodput.

define mild selfishness with respect to the cycling interval T_c, and introduce a *mild selfishness coefficient* γ as a multiplier that determines the duration of the interval when a node behaves in a mildly selfish manner, γT_c, herein $T_c = 10$ s. Nodes continue to duty cycle while they are mildly selfish.

Fig. 4 and 5 present the results for the Östermalm and Subway scenario with a participation rate of p = 10% and p = 50% respectively. (Similar results are observed for p = 100%.) We vary $\gamma \in \{0..25\}$; γ = 0 corresponds to a strictly selfish behavior, and γ = 25 corresponds to an interval of 250 s during which a node behaves in a mildly selfish manner after it has obtained all content items of interest. Since the mean sojourn time of nodes in the scenarios is approximately 300 s we do not investigate values beyond γ = 25. All values in Fig. 4 and 5 are normalized with respect to the energy consumption and goodput of an always-on system.

Across all scenarios the higher the coefficient γ, the closer the goodput becomes to the goodput of an always-on system, and achieving this goodput comes at a higher energy price. However, there are two interesting phenomena to note:

- At low values of γ an increase in goodput comes at a price of *decreased* energy consumption, as compared to the strictly selfish (γ = 0) case.
- At high values of γ a marginal increase in goodput comes at a price of a significant increase in energy consumption.

The decrease in energy consumption at lower values of the mild selfishness coefficient γ may at first seems counter-intuitive. To explore this phenomenon we study the *temporal nodal usefulness*, i.e. the time it takes from the moment a node downloads all content items of interest until the first moment that the same node shares data with another peer. The results in Fig. 6 show that across all scenarios and across all participation rates approximately 50% of the mildly selfish nodes deliver contents to a peer within the first 50 s (or γ = 5) after they have obtained all items of interest. Moreover, approximately 50% of the nodes in the area never deliver contents to a peer after they have obtained all items of interest (Fig. 7), and one third send only to a single peer, regardless of γ. (We note that although at higher γ the number of nodes that never share contents decreases, this decrease is marginal compared to the increase in energy consumption at the same value of the γ.)

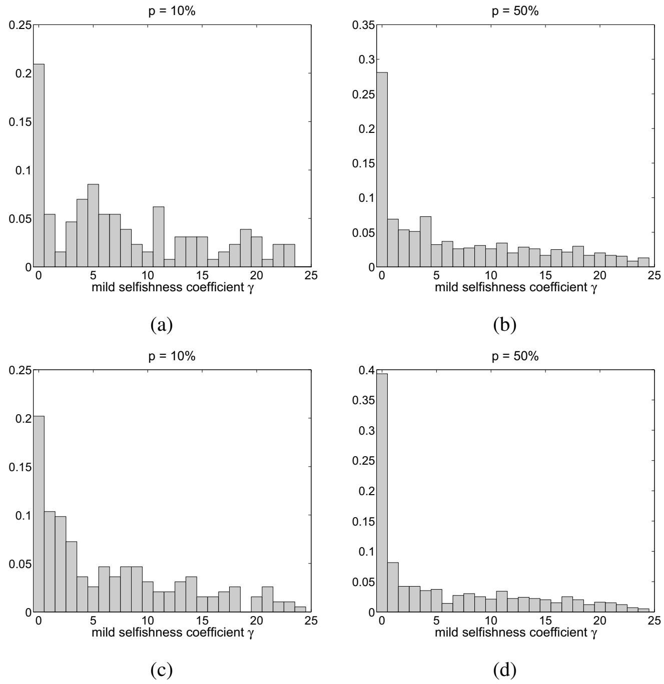
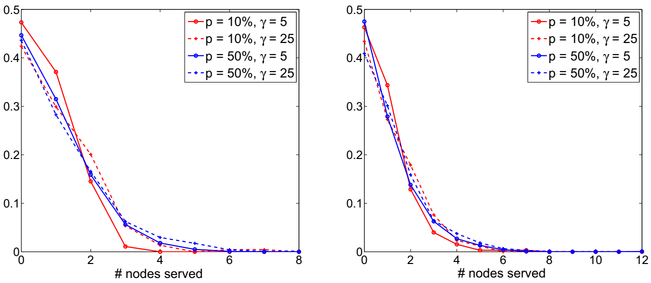


Fig. 6. Density of temporal nodal usefulness for the Östermalm (upper) and Subway (bottom) scenario with participation rate p = 10% and p = 50%.

IV. Related work

All work done in the area of mobile data offloading [1], [2], [3] concentrates on the performance benefits for the mobile operator, and thus considers nodes to act altruistically throughout the mobile data offloading process via direct D2D communication. However, from the perspective of battery-powered mobile devices, application throughput provided via opportunistic communication should be evaluated with respect to the energy cost for obtaining the data. Thus, nodes may be expected to apply different mechanisms for reducing energy cost, as well as adopting selfish behavior.

In [12], Hui et al. study the impact of different distributions of altruism on the throughput of opportunistic networks,



(a) (b)

Fig. 7. Content dissemination density for the (a) Östermalm and (b) Subway scenario under mild selfishness with coefficient γ and participation rate p.

and demonstrate that opportunistic networks are robust with respect to the form of altruism distribution. Social selfishness has been also evaluated by Li et al. [13] in terms of message delivery delay and replication to destination in the context of epidemic routing in delay tolerant networks. None of the studies considers the impact of selfishness on the energy consumption in nodes. Furthermore, selfishness is evaluated with respect to communication between specific source-destination pairs via (selfish) relays. Instead, our study evaluates selfishness in a content-centric environment in which the social effect is not related to previous social relationships between nodes, but instead is determined by their co-location in time and space.

Lu et al. [14] and Zhao et al. [15] propose incentive schemes for promoting altruism in opportunistic networks, however neither of the works discusses the implications in terms of energy consumption of altruistic behavior in battery powered devices. Ciobanu et al. [16] devise a mechanism for detecting and avoiding selfish nodes throughout the routing process in opportunistic networks. In contrast to these studies, we study selfishness in direct D2D communication in the context of mobile data offloading in order to decrease the energy consumption of participating devices.

V. Discussion and Future work

In this paper we examined the system performance in terms of application throughput (i.e. goodput) and energy consumption of direct D2D communication based on the 'store-carry-forward' paradigm in the context of mobile data offloading. We investigated realistic mobility scenarios such as grid of streets and subway station, and we introduced two types of selfish behavior: strict and mild selfishness, on top of a duty cycling scheme for energy savings in mobile devices. We demonstrated that under strict selfishness the energy consumption can be significantly reduced with some lost goodput, especially at low participation rates (low item popularity). We also showed that when combined with duty cycling strict selfishness performs similarly to an always-on approach that also has selfish nodes, but at a lower price in terms of energy consumption. Under mild selfishness, we showed that due to temporal nodal usefulness the energy consumption can be further decreased while at the same time increasing goodput performance when the mild selfishness coefficient is chosen appropriately.

Contrary to what has been investigated previously, we here argued that mobile data offloading should take into account not only the requirements of mobile operators, but also those of mobile devices. Thus, we see this work as a first step towards designing an intelligent solution for opportunistic mobile data offloading, and we believe such solution should involve duty cycling and selfishness as energy saving mechanisms in mobile devices. We also claim that maximizing goodput is no longer of highest priority. Instead, we believe that we should focus on decreasing energy consumption while delivering satisfactory user experience through direct D2D communication, and fetching potential missing content items via available WiFi or 3G/4G networks.

References

[1] B. Han, P. Hui, V. Kumar, M. Marathe, J. Shao, and A. Srinivasan, "Mobile data offloading through opportunistic communications and social participation," *Mobile Computing, IEEE Transactions on*, vol. 11, no. 5, pp. 821–834, May 2012.

[2] L. Xiaofeng, H. Pan, and P. Lio, "Offloading mobile data from cellular networks through peer-to-peer wifi communication: A subscribe-and-send architecture," *Communications, China*, vol. 10, no. 6, pp. 35–46, June 2013.

[3] Y. Li, M. Qian, D. Jin, P. Hui, Z. Wang, and S. Chen, "Multiple mobile data offloading through disruption tolerant networks," *Mobile Computing, IEEE Transactions on*, vol. 13, no. 7, pp. 1579–1596, July 2014.

[4] S. Guo, Y. Gu, B. Jiang, and T. He, "Opportunistic flooding in low-duty-cycle wireless sensor networks with unreliable links," in *Proc. MobiCom*, 2009.

[5] S. Bader and B. Oelmann, "Adaptive synchronization for duty-cycling in environmental wireless sensor networks," in *Proc. Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*, 2009.

[6] B. J. Choi and X. Shen, "Adaptive asynchronous sleep scheduling protocols for delay tolerant networks," *Mobile Computing, IEEE Transactions on*, vol. 10, no. 9, pp. 1283–1296, 2011.

[7] Y. Xi, M. Chuah, and K. Chang, "Performance evaluation of a power management scheme for disruption tolerant network," *Mob. Netw. Appl.*, vol. 12, no. 5, Dec. 2007.

[8] S. T. Kouyoumdjieva and G. Karlsson, "Energy savings in opportunistic networks," in *Proc. IEEE/IFIP WONS*, Obergurgl, Austria, 2014.

[9] Ó. Helgason, E. A. Yavuz, S. Kouyoumdjieva, L. Pajevic, and G. Karlsson, "A mobile peer-to-peer system for opportunistic content-centric networking," in *Proc. ACM SIGCOMM MobiHeld workshop*, 2010.

[10] Ó. R. Helgason and K. V. Jónsson, "Opportunistic networking in OMNeT++," in *Proc. SIMUTools, OMNeT++ workshop*, 2008.

[11] Ó. Helgason, S. Kouyoumdjieva, and G. Karlsson, "Opportunistic communication and human mobility," *Mobile Computing, IEEE Transactions on*, vol. 13, no. 7, pp. 1597–1610, July 2014.

[12] P. Hui, K. Xu, V. Li, J. Crowcroft, V. Latora, and P. Lio', "Selfishness, altruism and message spreading in mobile social networks," in *Proc. IEEE INFOCOM Workshops*, April 2009, pp. 1–6.

[13] Y. Li, P. Hui, D. Jin, L. Su, and L. Zeng, "Evaluating the impact of social selfishness on the epidemic routing in delay tolerant networks," *Communications Letters, IEEE*, vol. 14, no. 11, pp. 1026–1028, November 2010.

[14] R. Lu, X. Lin, H. Zhu, X. Shen, and B. Preiss, "Pi: A practical incentive protocol for delay tolerant networks," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 4, pp. 1483–1493, April 2010.

[15] G. Zhao, M. Chen, and X. Wei, "Ris: A reciprocal incentive scheme in selfish opportunistic networks," *Wireless Personal Communications, Springer US*, vol. 70, no. 4, pp. 1711–1734, 2013.

[16] R.-I. Ciobanu, C. Dobre, M. Dascălu, S. Trăusan-Matu, and V. Cristea, "Sense: A collaborative selfish node detection and incentive mechanism for opportunistic networks," *Journal of Network and Computer Applications*, vol. 41, pp. 240 – 249, 2014.