Accepted Manuscript

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PII: S0957-4174(12)00138-8
DOI: 10.1016/j.eswa.2012.01.120
Reference: ESWA 7414

To appear in: *Expert Systems with Applications*

Received Date: 10 April 2011
Accepted Date: 15 January 2012


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Swarm-oriented Mobile Services: Step towards Green Communication

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Abstract

Green communication is a new focus within the telecommunications industry, leading to various innovative ideas how to optimize communication in order to achieve energy savings. While the majority of those ideas target the transport layer of communication systems, this paper takes a different approach and proposes an innovation for the application layer by introducing a novel concept in the mobile telecom service provisioning: the swarm-oriented services. The presented proof-of-concept swarm-oriented mobile telecom service is called the Collaborative Downloading and its primary goal is to lower the mobile users’ overall energy consumption while downloading data. In order to enable this service, we designed the Self-organizing Market-based Algorithm (SOMA), which combines swarm intelligence (i.e. self-organization) and market-based (i.e. auctions) mechanisms, while the proof-of-concept implementation is based on multi-agent technology. Analytical results show that the proposed Collaborative Downloading service saved up to 76% of energy in mobile device batteries when compared with the current mobile data download practice (in a scenario with 6 mobile users whose mobile devices support GPRS and Bluetooth networking technologies).

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1. Introduction

The tremendous advances in the Information and Communication Technology (ICT) industry (e.g., Bieber et al. (2009); Knightson et al. (2005); Kwok (2009)) are recently supplemented by the idea of sustainability (discussed by Nash (2009)), what is popularly called the Green ICT (e.g., Feng et al. (2010); Ruth (2009)). Although people are passionate about the proliferation of ICT systems, they are not completely aware of the fact that the ICT infrastructure consumes a significant amount of energy causing negative effects both on electricity distribution grids and greenhouse gas emissions (Murugesan (2008); Wilbanks (2008)).

The green communication concept, as a part of a broader Green ICT initiative, inspired various innovative ideas how to optimize communication in order to increase energy efficiency. While the majority of those ideas are focused on the protocols and devices in the core network (e.g. Spyropoulos et al. (2008); Vuran & Akyildiz (2010)), this paper offers a different approach by proposing an innovation for protocols and devices in the access network. Although a lot of positive effects will emerge from introducing new regulations for the edge devices (e.g. strict energy efficiency specifications for personal computers as mentioned by Ruth (2009)), ICT companies should also make an effort towards green-aware service provisioning. A good example is given by Anastasi et al. (2010), where the Green Internet file sharing system is proposed, while the Energy Efficient Internet Project\(^1\) presented by Nordman & Christensen (2010) “addresses the increasingly critical need to improve the energy efficiency of the Internet by focusing on the primary and often neglected energy consumer, edge devices”.

The main idea behind the green communication concept is to find a way how to encourage people to change their behaviour in order to increase efficient use of current (and future) communication systems as presented by Cameron (2010). Guided by that idea, we envisioned a novel concept in the mobile telecom service provisioning process: the swarm-oriented services, both bio-inspired and bio-contributing services. The term swarm-oriented\(^2\) denotes that they are provisioned to a group comprised of similar users who

\(^{1}\) The Energy Efficient Internet Project, \url{http://www.csee.usf.edu/~christen/energy/main.html}

\(^{2}\) Swarm describes the behavior of an aggregate of animals with similar characteristics, often moving *en masse* or migrating in the same direction
collaborate in order to achieve a common goal. Swarm-oriented services are bio-inspired (Dressler & Akan (2010)) because they are characterized by the so called self-* properties (e.g. self-adjustment, self-awareness, self-configuring, self-healing, self-managing, self-monitoring, self-optimizing, self-organizing, self-protecting, self-situation), whose implementation is based on real world biological processes (e.g. trail formation in ants, bird flocking, fish schooling, pattern formation in bacteria, colony thermoregulation in honey bees). At the same time, swarm-oriented services are also bio-contributing because they are designed to reduce the users’ overall energy consumption when they are using that service. Besides, in the green communication concept, we found the motivation for modelling swarm-oriented services in the evolution from the Telco 1.0 service provisioning approach towards the Telco 2.0 service provisioning approach presented by Yoon (2007). This evolution can be best described with a shift from the linear services (i.e. traditional services where a mobile user cannot influence the predefined service provisioning process) towards the non-linear services (i.e. interactive services where mobile user participates in the mobile telecom service provisioning process, tailoring the service to her/his preferences, device and/or context as described by Feijóo et al. (2007)).

The paper is organized as follows. Section 2 describes perspectives for using swarm-oriented services in the mobile telecommunications domain, while section 3 presents the architecture and scenarios for the use of our proof-of-concept service, called Collaborative Downloading. Section 4 first describes the implementation of the Collaborative Downloading service as a multi-agent system and then demonstrates how the Collaborative Downloading service is provisioned. Finally, the same section presents an analytical model used for comparing time and energy consumption of user devices when operators apply the individual (i.e. current practice used for mobile data downloading) and collaborative approach (i.e. the Collaborative Downloading service) in service provisioning process. Section 5 concludes the paper and provides guidelines for future work.

2. Swarm-oriented services for mobile telecommunication users

Certainly biological processes can be used as an inspiration for solving problems in various computer-supported domains (e.g. engineering or telecommunications as described by Camazine et al. (2001)). Namely, aggregate motion in biological systems is called swarm behaviour while its application in
computer-supported systems is referred to as *Swarm Intelligence* (SI). The successful examples of applying swarm-like algorithms (e.g. Ant Colony Optimization (Chen et al. (2010)), Particle Swarm Optimization (Wang & Yang (2009)) and Flocking Clustering (Folino et al. (2009))) for solving real-world optimization problems in engineering and telecommunications include routing protocols (e.g. Di Caro et al. (2005); Kassabalis et al. (2001)), synchronization mechanisms (e.g. Bojic et al. (2012)), robotics\(^3\) and the travelling salesman problem (e.g. Balaprakash et al. (2009); Dorigo & Gambardella (1997)).

In addition to previously mentioned examples, we propose the application of SI for enabling a novel concept in the mobile telecommunication service provisioning domain – the swarm-oriented services. We already defined a swarm-oriented service as a telecom service that is provisioned to a group of mobile users who share certain similarities (e.g. similar preferences, devices and/or context) and who autonomously collaborate (e.g. Bojic et al. (2011); Conti et al. (2010); Wong (2010)) during the service provisioning process. Therefore, the first step in the process of provisioning swarm-oriented services is to group mobile users into clusters by taking into account user characteristics and preferences (i.e. user profiles) as well as service descriptions (i.e. service profiles). Once a group of mobile users is identified, it is necessary to design a mechanism for the autonomous coordination of collaboration between mobile users. This is where SI-based mechanisms impose themselves as an obvious solution.

The model of the proposed system for swarm-oriented mobile telecom service provisioning is based on the threefold view of mobile users described by Jung & Euzenat (2007) (see Fig. 1) and, consequently, consists of three layers: the *physical layer*, the *ontology layer* and the *social layer*.

2.1. The physical layer

The physical layer observes mobile users as individuals who are physically situated in the mobile network environment. Mobile users are connected to a telecom operator’s network via physical links and they own mobile devices which are able to communicate with the telecom operator’s base stations via wireless connections. Those mobile devices are also equipped with short-range communication technologies (e.g. Bluetooth or WiFi) which enable ad

Figure 1: The three-layered system model
hoc connections between users. The base stations are interconnected using wired links in the telecom operator’s core network.

2.2. The Ontology layer

In the computer and information science, the ontology is a formal representation of a set of concepts within a domain of interest, as well as of the relationships between those concepts as defined by Jepsen (2009). In our system, the ontology layer observes mobile users through their semantic profiles. Additionally, telecom operators maintain profiles of all available services (see Fig. 2). Each mobile user profile, as well as mobile telecom service profile, can be described by using a set of attributes referring to the created ontology.

In our system, a mobile user profile/service profile consists of five parts:

1. Identification (i.e. mobile device type/service name):

Figure 2: Mobile user profile and telecom service profile
2. Device hardware capabilities (i.e. available/necessary memory, screen resolution, etc.);
3. Device software capabilities (i.e. installed/necessary operating system, Web browser, Java version, etc.);
4. User preferences/service characteristics (i.e. preferred/implemented language, information type, delivery type, etc.); and
5. Context information (i.e. current/recommended user environment, location, current time, etc.)

A mobile user profile describes the user device characteristics, her/his preferences and current context, while a service profile presents the user device software and hardware characteristics needed to run the service, service characteristics and recommended provisioning context.

2.3. The Social layer

The social layer observes mobile users through swarms\(^4\) (i.e. clusters of similar users) – the telecom operator first filters mobile users according to a specific pre-criterion (e.g. location) and then includes them in a certain swarm if their profiles correspond with a defined criterion (e.g. the similarity between a mobile user and telecom service profile exceeds the given threshold).

3. Proof-of-concept service: Collaborative Downloading

Our proof-of-concept swarm-oriented mobile telecom service is called the Collaborative Downloading and its purpose is to increase energy efficiency of the mobile telecom service provisioning process. This is important for mobile users because limited energy supply is one of the main obstacles for frequent usage of advanced mobile telecom services. Also, it is important for telecom operators because it enables service provisioning compliant with the green communication concept.

Today, when a mobile user wants to download certain content to her/his mobile device, she/he is not aware of other mobile users interested in the same content. Consequently, each mobile user communicates only with a service server (e.g. a telecom operator’s server or a 3\(^{rd}\) party provider’s server) and

\(^4\)During the provisioning of a certain swarm-oriented service (e.g. Collaborative Downloading) all users clustered into one group constitute a swarm (e.g. Swarm 1 in Fig. 2 – consequently, each user is a swarm individual from the social layer viewpoint.
downloads the desired content via mobile network technology. We refer to this standard approach of the mobile telecom service provisioning process as the individual approach (since there is no collaboration between mobile users – every user acts as an individual). The basic idea of our novel approach (i.e. collaborative approach) is that mobile users, who are interested in the same content, collaborate and download the desired content together. On the service server, the content is divided into several parts so that each part can be downloaded independently via mobile network technology and afterwards exchanged with other interested mobile users via mobile ad hoc network technology. Mobile users compete on the ”Collaborative Downloading market” to determine which parts of the requested content to download directly from the service server and which parts to exchange with other mobile users in the same swarm (the exchange of content parts is preceded by a series of auctions used to determine the sequence of the exchange).

We will first define the terminology by presenting the generic Collaborative Downloading scenario and architecture. Afterwards, we will present the Self-organizing Market-based Algorithm (SOMA) as a solution for coordinating collaboration among swarm individuals during the provisioning of the Collaborative Downloading service.

3.1. Generic Collaborative Downloading scenario

The main idea of the collaborative approach is to identify a set of \( n \) mobile users who are physically at a smaller distance to each other (e.g. 10 m – the range of Bluetooth) and who are interested in the same content. Each of \( n \) mobile users downloads only a part of the requested content via mobile network (e.g. General Packet Radio Service, GPRS or Universal Mobile Telecommunications System, UMTS) and shares it with other \( n - 1 \) mobile users within the newly formed mobile ad hoc network via short-range communication technology (e.g. Bluetooth or WiFi). The collaborative approach is enabled by filtering mobile users by their physical location and clustering (for more details see Vrdoljak et al. (2010)) those mobile users into groups of similar interest (i.e. swarms). The most significant benefit of the proposed service refers to the fact that the Bluetooth (WiFi) network is more energy-efficient than the GPRS (UMTS) network. Furthermore, communication in the Bluetooth (WiFi) network is virtually free of charge for mobile users, as opposed to communication in the GPRS (UMTS) network. Also, switching communication from the GPRS (UMTS) network to the Bluetooth (WiFi) network releases GPRS channels (UMTS bandwidth). Those resources can
Table 1: Energy consumption and throughput ratios (Bluetooth vs. GPRS and WiFi vs. UMTS)

<table>
<thead>
<tr>
<th>Energy consumption / throughput ratio</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption ratio Bluetooth/GPRS</td>
<td>0.045</td>
</tr>
<tr>
<td>Throughput ratio Bluetooth/GPRS</td>
<td>0.550</td>
</tr>
<tr>
<td>Energy consumption ratio WiFi/UMTS</td>
<td>0.389</td>
</tr>
<tr>
<td>Throughput ratio WiFi/UMTS</td>
<td>12.500</td>
</tr>
</tbody>
</table>

then be put to further use for other mobile users, thus decreasing the mobile telecom service provisioning cost for both telecom operators and mobile users. The comparison of Bluetooth vs. GPRS energy consumption (data gathered from Fryman et al. (2003); O’Hara et al. (2006); Zanella et al. (2003)) as well as the comparison of WiFi vs. UMTS energy consumption (data gathered from Kassinen et al. (2009)) is given in Table 1, together with the comparison of corresponding data rates (namely, effective throughput perceived from the application perspective) (data gathered from Chevul et al.).

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5When calculating the energy consumption and throughput for mobile network technology (i.e., GPRS and UMTS), only download is considered. However, when calculating the energy consumption and throughput for short-range communication technology (i.e., Bluetooth and WiFi) the average of download and upload data rates is used. The reason for that is twofold. Firstly, the Collaborative Downloading service uses mobile network technology only for download of content parts (upload traffic needed for communication initialization can be neglected). Secondly, while users are exchanging content parts in an ad hoc network short-range communication technology is evenly used both for upload and download of content parts since one user uploads the content part directly to the other user which has to download it.

6J2ME Bluetooth Programming: [http://www.nowires.org/Presentations-PDF/AndreKpresentasjon.pdf](http://www.nowires.org/Presentations-PDF/AndreKpresentasjon.pdf)
3.2. Generic Collaborative Downloading architecture

The architecture of the proposed system is illustrated in Fig. 3. Let $Z = \{z_1, \ldots, z_N\}$ denote a set of mobile users who are subscribers of a certain telecom operator and let $X = \{x_1, \ldots, x_i, \ldots, x_j, \ldots, x_n\}$ denote a set of mobile users in one mobile ad hoc network (i.e. swarm). The set $X$ is always a subset of the set $Z (X \subset Z)$, while $n = |X|$ (in Fig. 3 value $n = 4$). Calculation of the set $X$ from the set $Z$ can be done in various ways. One possible way, based on the semantic matchmaking between mobile user and service profile, will be proposed in Section 4.2. In Fig. 3 we can see that content is divided into smaller parts and stored on the service server. Let $Y = \{y_1, \ldots, y_k, \ldots, y_m\}$ denote the set of content parts (in Fig. 3 value $m = 5$).

In the proposed system, there are two possible modes of communication: via mobile network technology (i.e. GPRS and UMTS) and via short-range
communication technology (i.e. Bluetooth and WiFi). Mobile devices communicate with the service server via mobile network using *Session Initiation Protocol* (SIP) messages as control messages and *Hypertext Transfer Protocol* (HTTP) protocol for content download.

3.3. SOMA: Self-organizing Market-based Algorithm for enabling collaboration among swarm individuals

The algorithm which enables the collaboration among swarm individuals is referred to as the SOMA. In the first phase of the SOMA, the "Collaborative Downloading market" is formed and swarm individuals that participate on that market download content parts from the service server. They are going to exchange those content parts later on. The second phase of the SOMA is comprised of a series of auctions in which swarm individuals interact on the formed market in order to obtain missing content parts. Among other allocation mechanisms, we chose auctions since they are defined as a market institution that acts in pursuit of a set of pre-defined rules that are used to compute the desired economic outcome (i.e. high allocation efficiency) of social interactions as defined by Wurman et al. (2002). In the market formation phase each swarm individual acts as a buyer while in the auctions phase each swarm individual simultaneously acts as a buyer and a seller.

3.3.1. Phase one: SOMA market formation

Inputs to the first phase of the SOMA are the sets $X$ and $Y$, while the output is defined as an association of each element in the set $Y$ with exactly one swarm individual from the set $X$ – this is the swarm individual who has to download the corresponding part of the requested content directly from the service server via mobile network technology and then act as the initial seller of that content part in the second phase of the SOMA. This is also the reason why this first step of the SOMA is called the *market formation*.

SOMA’s market formation phase begins with each swarm individual $x_i$ sending her/his current device status parameters to the service server which than calculates user *device status* $ds(x_i)$ and determines how many content parts will each swarm individual download from it via mobile network technology. The device status is defined by the following equation:

$$ds(x_i) = w_{bc}bc(x_i) + w_{ss}ss(x_i), \forall x_i \in X$$  \hspace{1cm} (1)

where

$$w_{bc} + w_{ss} = 1$$  \hspace{1cm} (2)
The variable $bc(x_i) \in [0, 100]$ indicates the battery charge level and $ss(x_i) \in [0, 100]$ the signal strength level of the swarm individual $x_i$’s mobile device, while $w_{bc1}$ and $w_{ss}$ are non-negative constants that define the importance of the battery charge level and the signal strength level, respectively. While the $bc(x_i)$ and $ss$ values are individual characteristics of every particular swarm individual $x_i$, $w_{bc1}$ and $w_{ss}$ are predefined by the telecom operator and are common to all swarm individuals from the set $X$.

After calculating the device status $ds(x_i)(\forall x_i \in X)$ of all swarm individuals who will participate in the newly formed market, by using the equation (3) the service server determines the number of content parts $np(x_i)$ which each swarm individual $x_i$ has to download directly from it:

$$np(x_i) = \text{round}(m \frac{ds(x_i)}{\sum_{j=1}^{n} ds(x_j)}), \forall x_i \in X,$$

where

$$\sum_{i=1}^{n} np(x_i) = m. \tag{4}$$

Once the number of content parts $np(x_i)$ is calculated for all swarm individuals $x_i$ from the set $X$, the content download can start. It is possible that some swarm individuals download more than one content part (when $n < m$) and it is also possible that some swarm individuals do not have to download content parts from the service server (when $n > m$). Anyhow, it is important to note that the entire content will be in the mobile ad hoc network at the end of the first SOMA phase as determined by equation (4). The Algorithm 1 describes, from the buyer’s perspective, the first phase of the SOMA in pseudo code.

**Algorithm 1:** Buyer’s behaviour in the first phase of SOMA

1. calculate device status $ds(x_i)$ /* using equation (1) /*
2. send device status $ds(x_i)$ to the service server
3. download $np(x_i)$ content parts from the service server

3.3.2. Phase two: SOMA auctions

The input to the SOMA auctions phase is the output from the SOMA market formation phase (i.e. association of each content part with exactly
one swarm individual), while the output from the SOMA auctions phase is defined as the state of the system in which each swarm individual from the set $X$ possesses all content parts from the set $Y$ and is therefore able to put together the requested content. In this phase of the SOMA, content parts are exchanged between swarm individuals via short-range communication technology. Each swarm individual that possesses at least one content part acts as a seller in the auction and receives asks from other swarm individuals acting as buyers. At the same time, each swarm individual missing at least one content part acts as a buyer in the auction and sends asks to other swarm individuals for the content parts she/he needs. Each swarm individual $x_i$ conducts one auction for each content part $y_k$ she/he is missing. The total number of SOMA auctions $t$ that are going to be held equals to the product of the total number of content parts $m$ and the total number of swarm individuals $n$ decreased by 1 since all the parts were downloaded once in the SOMA market formation phase, i.e. $t = m \times (n - 1)$.

Running several auctions at the same time would cause problems since the values of attributes which are used to determine the winner of the auction can change significantly between the moment when a seller sends her/his asks and the moment when a buyer declares a winner of a certain auction. For this reason the SOMA auctions are conducted in a round robin manner, while the schedule is determined from the order in which swarm individuals accepted proposals for participation in the Collaborative Downloading service.

Each SOMA auction can be categorized as a reverse multi-attribute auction (e.g. Keeney & Raiffa (1993); Petric & Jezic (2010)) since there is only one buyer that negotiates the exchange of a single content part with multiple sellers while the decision is made based on more than one attribute (i.e. sellers’ battery charge level and the number of previously exchanged content parts with a particular seller). Therefore, we define the SOMA auction as a tuple $< x_i, X_i, Y_i, O_i, u >$, where:

1. the swarm individual $x_i$ acts as a buyer in the ongoing auction;
2. the set $X_i = x_1, \ldots, x_j, \ldots, x_p$ denotes the set of swarm individuals that act as sellers in swarm individual $x_i$’s auction ($X_i \subseteq (X \setminus x_i); p \leq n - 1$);
3. the set $Y_i = y_1, \ldots, y_k, \ldots, y_r$ where $Y_i \subseteq Y; r \leq m$ denotes the contents parts that the buyer $x_i$ is still missing and is trying to obtain one of them in the ongoing auction;
4. the set $O_i = o_{i1}, \ldots, o_{ij}, \ldots, o_{ip}$ where $o_{ij} = x_i, x_j, y_k$ denotes seller $x_j$’s bid containing the content part $y_k \in Y_i$ which she/he is offering to the
buyer $x_i$ in the ongoing auction; and
5. $u$ is the winner determination function.

As shown in the Fig. 4, at the beginning of an auction, the buyer $x_i$ sends an ask containing a list of content parts she/he is missing $Y_i$ to all sellers from the set $X_i$. Each seller $x_j$ places a new bid $o_{ij}$ offering the content part with the smallest delivery cost. After receiving all bids, the buyer calculates the total exchange cost $u(o_{ij})$ for the bid $o_{ij}$ offered by the seller $x_j$ as follows:

$$u(o_{ij}) = w_{dc} dc(x_j, y_k) + w_{pi} pi(x_i, x_j),$$
\forall o_{ij} \in O_i, \forall x_j \in X_i, w_{dc} + w_{pi} = 1 \quad (5)$$

where $dc(x_j, y_k)$ represents swarm individual $x_j$'s delivery costs for the bid $o_{ij}$ containing the content part $y_k$ and $pi(x_i, x_j)$ denotes the prior interaction between the buyer $x_i$ and the seller $x_j$. We assume the existence of mutual preferential independence between all attributes used for determining the total exchange cost so (according to Keeney & Raiffa (1993)) the function $u(o_{ij})$ can be defined as an additive scoring function.

Seller $x_j$'s delivery cost $dc(x_j, y_k)$ for the bid $o_{ij}$ which contains the content part $y_k \in Y_i$ is calculated as follows:

$$dc(x_j, y_k) = w_{bc2} \frac{100 - bc_j}{100} + w_{af} f_{j,q}(y_k) \quad (6)$$

where

$$w_{bc2} + w_{af} = 1 \quad (7)$$

The variable $f_{j,q}(y_k) \in [0, 1]$ represents the antipheromone\(^7\) value for swarm individual $x_j$’s content part $y_k$ in the current auction $q \in [1, t]$, while $w_{bc2}$ and

\(^7\)In Ant Colony Optimization, ants use pheromones for indirect communication. Chemical pheromone trials enable them to find shorter paths between their nest and food. As the time passes pheromones evaporate so a shorter path which is visited by more ants will have a higher pheromone density (this can be described as a positive feedback loop) than the longer path. In our system we use antipheromones to model a negative feedback loop instead of a positive one. An antipheromone value is assigned to each content part on the market. As time passes, the antipheromone also evaporates and finally disappears. By using this kind of negative feedback loop, each swarm individual distributes those content parts which have the lowest antipheromone value and helps to avoid the situation in which only the swarm individual that downloaded a certain content part from the service server distributes it to other individuals in the swarm.
Figure 4: An example of the SOMA auction
are weights used to define the importance of the battery charge level and the antipheromone value to the seller $x_j$, respectively. The antipheromone value for the content part $y_k$ that the seller $x_j$ offers in the auction $q$ is determined as:

$$af_{j,q}(y_k) = \begin{cases} 
0, & \text{if the seller } x_j \text{ never sold } y_k \\
1, & \text{if the seller } x_j \text{ sold } y_k \text{ in the previous auction } q - 1 \\
af_{j,q-1}(y_k) - af_{j,dec}(y_k), & \text{otherwise}
\end{cases} \tag{8}$$

At the beginning of the SOMA auctions phase the antipheromone values of all content parts are set to the lowest possible value (i.e. $af_{j,q}(y_k) = 0, \forall y_k \in Y, \forall x_j \in X$). The antipheromone value $af_{j,q}(y_k)$ is set to the highest possible value (i.e. 1) in the current auction $q$ if the seller $x_j$ sold the content part $y_k$ in the previous auction $q - 1$. As time passes, the antipheromone value decreases. For each content part $y_k$ the seller $x_j$ calculates the antipheromone decrement value $af_{j,dec}(y_k)$ as follows:

$$af_{j,dec}(y_k) = \frac{1}{t - q_{sold}(y_k)} \tag{9}$$

where $t$ is the total number of auctions that are held in the SOMA auctions phase while the $q_{sold}(y_k)$ is the serial number of the auction in which the seller $x_j$ sold the content part $y_k$. The antipheromone value decreases slower for the content parts that are sold in earlier auctions and it will be set to the lowest value (i.e. 0) at the end of the SOMA auctions phase. This way, seller $x_j$’s delivery cost $dc(x_j, y_k)$ for the content part $y_k$ are higher than the delivery cost for the content part $y_k$ of other sellers (i.e. $dc(x_j, y_k) > dc(x_i, y_k)$ where $x_i \in X \setminus x_j$) so the content part $y_k$ will be further distributed in the swarm by other sellers. At the same time, the seller $x_j$ will distribute other content parts that it downloaded from the service server or bought from other swarm individuals.

Buyer $x_i$’s prior interaction with the seller $x_j$ is calculated as follows:

$$pi(x_i, x_j) = w_{pb} \frac{pb(x_i, x_j)}{m} + w_{ps} \frac{m - ps(x_i, x_j)}{m} \tag{10}$$

where

$$w_{pb} + w_{ps} = 1 \tag{11}$$
The variable \( pb(x_i, x_j) \) represents the number of content parts that the buyer \( x_i \) already bought from the seller \( x_j \) and \( ps(x_i, x_j) \) represents the number of content parts that the buyer \( x_i \) already sold to the seller \( x_j \). \( m \) represents the number of parts the requested content is divided in, while \( w_{pb} \) and \( w_{ps} \) are weights used to define the importance of \( pb(x_i, x_j) \) and \( ps(x_i, x_j) \) to the buyer \( x_i \), respectively. The purpose of the prior interaction attribute is to ensure that swarm individuals exchange parts with the majority of the group and not just with certain individuals. The winner determination function takes as input the total exchange cost \( u(o_{ij}) \) of all received offers \( O \) and determines the winning offer as follows:

\[
 u = \arg \min_{o_{ij} \in O_i} u(o_{ij})
\]  

(12)

Algorithm 2 and Algorithm 3 describe the second phase of the SOMA in a pseudo code.

**Algorithm 2:** Buyer \( x_i \)'s behaviour in the second phase of the SOMA

```plaintext
for l ← 1 to m - np(x_i) do
    start new auction;
    collect bid \( o_{ij} \) and \( dc(x_j, y_k) \) from \( x_j (\forall x_j \in X_i) \);
    bestOffer = -1;
    foreach \( o_{ij} \) do
        calculate \( pi(x_i, x_j) \) \( \text{/ using formula (10) } \)
        calculate \( u(o_{ij}) \) \( \text{/ using formula (5) } \)
        if \( u(o_{ij}) < \text{bestOffer} \) then
            bestOffer = \( o_{ij} \);
        if \( \text{bestOffer} \neq -1 \) then
            buy \( \text{bestOffer} \);
```

3.4. A real-world application of the Collaborative Downloading service

Our proof-of-concept Collaborative Downloading service can be used as a real world application that is based on Bluetooth or WiFi communication even though it has several limitations. For instance, in order to establish communication, mobile users have to be in close proximity to each other (i.e. within a range of 10 m as determined by the Bluetooth specifications).
Algorithm 3: Seller $x_j$’s behaviour in the second phase of the SOMA

\begin{algorithm}
\begin{algorithmic}
\For {$q \leftarrow 1$ \textbf{to} $q \leq m(n-2)np(x_j)$}
\State receive call for participation;
\State $bestOffer = -1$;
\For {$l \leftarrow 1$ \textbf{to} $l \leq np(x_j)$}
\State calculate $dc(x_j, y_l) \quad \text{*/ using formula (6) */}$
\If {$dc(x_j, y_l) < bestOffer$}
\State $bestOffer = dc(x_j, y_l)$;
\EndIf
\EndFor
\If {$bestOffer \neq -1$}
\State buy $bestOffer$;
\EndIf
\EndFor
\end{algorithmic}
\end{algorithm}

Additionally, in order to establish collaboration, users’ interests and time frames for using the service have to match (i.e. users have to be interested in the same content at approximately the same time) since new users cannot join a group once the market formation phase is completed. nor can they leave the group before the end of the SOMA auctions phase.

Since those limitations (i.e. small distance, same time frame and interests) may seem to be significant disadvantages of our approach, in this paragraph we illustrate two feasible real world examples for our collaborative approach: a football match and cinema viewing. Fig. 5 shows the seating layouts at a sports stadium and at a cinema. Within a range of 10 m, there are approximately 40 seats at a stadium and 30 seats in a cinema. It is our assumption that at least four users seated on those places could be interested in same content within the same time frame. Moreover, since mobile users are expected to be in their seats during the play or match, we assume that they form a fixed group and do not leave it until the end of the play or match (i.e. there is enough time for successful service provisioning). For future work, we plan to investigate the situation in which mobile users can form flexible groups, where they would be able to leave a collaborating group before the service provisioning is completed. Finally, due to Bluetooth’s short-range, multiple and mutually independent Bluetooth ad hoc networks could be created simultaneously at the same stadium or cinema. This could reduce the occurrence of the service (un)availability problem which appears during peak hours when there is an insufficient amount of available mobile network resources in one mobile cell (e.g. a limited number of channels).
3.4.1. A football match

When people go to a football match at a sports stadium, they surely share one common interest, i.e. the sporting event they came to watch. They are also present at the same location at the same time. In the USA, there are big screens at the stadiums where people can watch replays of incredible opportunities/failures during a match. However, in some other countries (e.g. Croatia) there are no big screens at the stadiums. In cases like this one, it would be simpler and cheaper for the organizers of such events to use the described collaborative approach in order to deliver video clips containing replays of the game directly to users’ mobile devices, than to buy expensive screens.

3.4.2. A cinema viewing

At a cinema viewing, before the actual film starts, the audience is shown several movie trailers on the cinema screen. After they see a certain movie trailer, some of them might decide to download that trailer to their mobile devices and afterwards share it with their friends or family. By using the collaborative approach they could save some energy in their mobile device

Figure 5: The sports stadium and the cinema seating layout
batteries, as well as lower their expenses.

4. The Collaborative Downloading service: the implementation, demonstration and efficiency analysis

In this section we present implementation details of our proof-of-concept service and explain the demonstration procedure. At the end of this section we calculate the time and energy efficiency of the Collaborative Downloading service by conducting an analytical comparison with the current mobile data download practices.

4.1. The implementation of the Collaborative Downloading service

The proposed proof-of-concept service is implemented by using software agents (see Fig. 6). Software agents (Fasli (2007); Nwana (1996)) are programs that perform complex information and communication actions over the web on behalf of their owners. They reduce the time necessary to carry out certain personal or business tasks thus enhancing work efficiency (Podobnik et al. (2008)). Software agents have proven to be very suitable for mobile user profile management as (e.g. Bonnin et al. (2009); Frkovic et al. (2008); Panayiotou & Samaras (2004)) and telecom processes enhancements (e.g. Podobnik et al. (2009)).

There are five types of agents in the proposed multi-agent system: Swarm Individual Agents (SIAs), Repository Agent (RA), Server Agent (SA), ACL-to-SIP Agent (ASA) and SIP-to-ACL Agent (SAA). The SIAs, which represent mobile users (i.e. swarm individuals) during the Collaborative Downloading service provisioning, receive Agent Communication Language (ACL) messages from the SAA and ASA. While the communication between the multi-agent system and swarm individuals is based on SIP messages, the communication between agents in the multi-agent system is based on ACL messages. In order to enable the communication between swarm individuals and their agents (i.e. SIAs), the SAA converts SIP messages to ACL messages and the ASA converts ACL messages to SIP messages.

The SA manages the SOMA market formation phase by calculating the number of content parts $np(x_i)$ that each user $x_i$ has to download and performing the procedure for swarm formation (see section 4.2.1). The RA receives user profiles from the SA and stores them into a semantic database. Also, the RA keeps track of all available telecom services and provides a list...
Figure 6: The multi-agent system implementing the Collaborative Downloading service
of service profiles on SA’s request. The SIAs represent mobile users and participate in the SOMA market formation phase by providing its user’s device status information to the SA. They also participate in the SOMA auctions phase simultaneously acting as sellers and buyers of content parts (see Algorithms 1, 2, 3).

The described multi-agent system is implemented by using the Java Agent DEvelopment Framework (JADE¹) described by Bellifemine et al. (2007). JADE simplifies the implementation of multi-agent systems through a middleware that complies with the Institute of Electrical and Electronics Engineers (IEEE) Foundation for Intelligent Physical Agents (FIPA) specifications and through a set of graphical tools that support the debugging and deployment processes.

4.2. The demonstration of the Collaborative Downloading service

The prerequisite for the provisioning of the Collaborative Downloading service is to identify a set of \( n \) swarm individuals who are in a close proximity to each other, who are interested in the same multimedia content and who are willing to collaborate with other users. When a swarm is formed, the Collaborative Downloading service is provisioned (i.e. the coordination of swarm individuals).

4.2.1. The swarm formation

The swarm formation consists of the following phases:

Step 1. A mobile user is interested in downloading certain multimedia content (e.g. a movie trailer that the user would like to watch while she/he is waiting in line to buy cinema tickets). This mobile user is referred to as the initiating user. The download of the multimedia content for which the initiating user showed interest is referred to as the requested mobile telecom service.

Step 2. Filtering mobile users which are at approximately the same physical location as the initiating user. Telecom operators calculate the physical distance between mobile users form the users’ context information (i.e. current location) stored in their user profiles.

Step 3. Extracting those users that are interested in the requested mobile telecom service from the group of filtered mobile users and organizing

¹http://jade.tilab.com
them into a new group. This is achieved by using the following actions:

(a) Calculating the similarities between the profile of the requested mobile telecom service and the profiles of each filtered mobile users (i.e. semantic matchmaking⁹, see Table 2);

(b) Ranking mobile users in a descending order based on the semantic matchmaking of their profiles with the profile of the requested mobile telecom service (see Table 3);

Step 4. Mobile users that are currently on the same physical location as the initiating user and whose results of the semantic matchmaking of their mobile user profiles and the requested mobile telecom service profile are greater than a predefined threshold (e.g. 45% of the highest similarity result) are clustered into the same group – they are potential swarm individuals.

Step 5. Enquiring all mobile users in the identified group about their interest for collaborating in order to download multimedia content requested by the initiating user. The service server sends a message with the proposal for collaboration to all possible candidates. Each mobile user can answer with "yes" or "no" to the proposal. The initiating user and the mobile users who answered positively form a swarm and afterwards collaborate to download the desired content.

4.2.2. The coordination of swarm individuals

As shown in Fig. 6, in the presented Collaborative Downloading service demonstration scenario, there are four mobile users \( n = 4 \), mobile users \( x_1-x_4 \) interested in the multimedia content that is stored on the service server and divided into five parts \( m = 5 \), parts \( y_1-y_5 \). Data in Table 4 shows the battery charge \( bc(x_i) \) and signal strength \( ss(x_i) \) levels of each mobile device in the created ad hoc network where \( bc(x_i) \in [0, 100] \) and \( ss(x_i) \in [0, 100] \).

⁹The existence of semantic descriptions of the mobile user and the mobile telecom service profiles (Fig. 2) enables the similarity calculation (i.e. semantic matchmaking) between them. Semantic matchmaking is the process of comparing two objects represented by their semantic profiles. In our case, we compare the profile of a mobile user with the profile of a mobile telecom service and rate their similarity. The result of the comparison is a real number between 0 and 1. The details about our semantic matchmaking algorithm are described by Podobnik & Lovrek (2010).
Table 2: Semantic matchmaking

<table>
<thead>
<tr>
<th>User Attribute</th>
<th>Value</th>
<th>Service Attribute</th>
<th>Value</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>hasAvailableMemory</td>
<td>18000</td>
<td>hasSize</td>
<td>16000</td>
<td>1.00</td>
</tr>
<tr>
<td>hasVScreenResolution</td>
<td>320</td>
<td>hasVResolution</td>
<td>300</td>
<td>1.00</td>
</tr>
<tr>
<td>hasHScreenResolution</td>
<td>380</td>
<td>hasHResolution</td>
<td>400</td>
<td>0.95</td>
</tr>
<tr>
<td>hasOs</td>
<td>BasicOs</td>
<td>hasOs</td>
<td>BasicOs</td>
<td>1.00</td>
</tr>
<tr>
<td>hasBrowser</td>
<td>Fennec</td>
<td>hasBrowser</td>
<td>noMatter</td>
<td>1.00</td>
</tr>
<tr>
<td>hasJavaVersion</td>
<td>15</td>
<td>hasJavaVersion</td>
<td>15</td>
<td>1.00</td>
</tr>
<tr>
<td>hasPreferredLanguage</td>
<td>English</td>
<td>hasLanguage</td>
<td>English</td>
<td>1.00</td>
</tr>
<tr>
<td>hasPreferredFormat</td>
<td>Mp3</td>
<td>hasFormat</td>
<td>AdvancedFormat</td>
<td>0.20</td>
</tr>
<tr>
<td>hasPreferredDeliveryType</td>
<td>NonStreaming</td>
<td>hasDeliveryType</td>
<td>Streaming</td>
<td>0.50</td>
</tr>
<tr>
<td>hasEnvironment</td>
<td>InnerSpace</td>
<td>hasEnvironment</td>
<td>OuterSpace</td>
<td>0.50</td>
</tr>
<tr>
<td>hasLocation</td>
<td>Ina</td>
<td>hasLocation</td>
<td>Lisinski</td>
<td>0.13</td>
</tr>
<tr>
<td>atTime</td>
<td>Night</td>
<td>atTime</td>
<td>NoMatter</td>
<td>1.00</td>
</tr>
<tr>
<td>Similarity</td>
<td></td>
<td></td>
<td></td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 3: Mobile user ranking

<table>
<thead>
<tr>
<th>Rank</th>
<th>User</th>
<th>Similarity</th>
<th>Potential group members</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>User₁ (x₁)</td>
<td>0.754</td>
<td>yes</td>
</tr>
<tr>
<td>2.</td>
<td>User₂ (x₂)</td>
<td>0.650</td>
<td>yes</td>
</tr>
<tr>
<td>4.</td>
<td>User₃ (x₃)</td>
<td>0.480</td>
<td>yes</td>
</tr>
<tr>
<td>3.</td>
<td>User₄ (x₄)</td>
<td>0.523</td>
<td>yes</td>
</tr>
<tr>
<td>7.</td>
<td>User₅</td>
<td>0.315</td>
<td>no</td>
</tr>
<tr>
<td>8.</td>
<td>User₆</td>
<td>0.285</td>
<td>no</td>
</tr>
<tr>
<td>6.</td>
<td>User₇</td>
<td>0.332</td>
<td>no</td>
</tr>
<tr>
<td>5.</td>
<td>User₈</td>
<td>0.402</td>
<td>no</td>
</tr>
</tbody>
</table>
Table 4: The battery charge and signal strength levels at moments $t_0$ and $t_2$

<table>
<thead>
<tr>
<th>Values</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bc(x_i)$</td>
<td>68</td>
<td>58</td>
<td>26</td>
<td>20</td>
</tr>
<tr>
<td>$ss(x_i)$</td>
<td>92</td>
<td>92</td>
<td>54</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 5: Antipheromone values at the moments $t_1$ and $t_2$

<table>
<thead>
<tr>
<th>Values</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_1$</td>
<td>0</td>
<td>100</td>
<td>31</td>
<td>35</td>
</tr>
<tr>
<td>$y_2$</td>
<td>0</td>
<td>66</td>
<td>6</td>
<td>22</td>
</tr>
<tr>
<td>$y_3$</td>
<td>0</td>
<td>56</td>
<td>51</td>
<td>1</td>
</tr>
<tr>
<td>$y_4$</td>
<td>68</td>
<td>0</td>
<td>11</td>
<td>89</td>
</tr>
<tr>
<td>$y_5$</td>
<td>12</td>
<td>1</td>
<td>89</td>
<td>74</td>
</tr>
</tbody>
</table>

The moment $t_0$ denotes the beginning of the first phase of the SOMA, the moment $t_1$ denotes the end of the SOMA market formation phase and the moment $t_2$ denotes a moment in the second phase of the SOMA after several auctions have already been conducted. For each mobile user $x_i$, the service server calculates the number of parts $np(x_i)$ that she/he must download by using the equation (1) with the associated parameters set to $w_{bc1} = w_{ss} = 0.5$, the equation (3) and the data from Table 4. The results of the SOMA market formation phase are as follows: $np(x_1) = 2, np(x_2) = np(x_3) = np(x_4) = 1$. Afterwards, mobile users download the designated parts directly from the service server via GPRS. The distribution of downloaded content parts at the end of the SOMA market formation phase (i.e. the moment $t_1$) is shown in Table 5 and their antipheromone values are set to the lowest possible value (i.e. 0). During the second phase of the SOMA mobile users exchange content parts via Bluetooth while the exchange schedule is determined by a series of auctions.

At the moment $t_2$ the mobile user $x_2$ starts a new auction for the content parts she/he is missing (i.e. content parts $y_4$ and $y_5$). The sellers that have at least one of those parts calculate the associated delivery costs by using the equation (6) with the associated parameters set to $w_{bc2} = w_{af} = 0.5$. 

25
Table 6: The number of bought and sold content parts for the mobile user \( x_2 \) at the moment \( t_2 \)

<table>
<thead>
<tr>
<th>Values</th>
<th>( x_1 )</th>
<th>( x_3 )</th>
<th>( x_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pb(x_2) )</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( ps(x_2) )</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

and the data from Table 4 and Table 5. The buyer (i.e., mobile user \( x_2 \)) receives sellers’ delivery cost: \( dc(x_1, y_5) = 27 \), \( dc(x_3, y_4) = 24 \), \( dc(x_4, y_5) = 70 \) and afterwards calculates the prior interaction with those sellers by using the equation (6) with the associated parameters set to \( w_{pb} = w_{ps} = 0.5 \) and the data from Table 6.

Finally, the mobile user \( x_2 \) calculates the total exchange cost by using the equation (5):

\[
u(x_2, x_1, y_5) = 30.5, u(x_2, x_3, y_4) = 26, u(x_2, x_4, y_5) = 72.\]

The cost \( u(x_2, x_3, y_4) \) is the lowest, so mobile user \( x_2 \) decides to obtain the part \( y_4 \) via Bluetooth from the mobile user \( x_3 \).

4.3. Analytical model for energy and time consumption of user devices

In this section we define an analytical model for calculating energy and time consumption of user devices during the mobile telecom service provisioning process. The model differentiates between the individual and collaborative approach that the operator uses in the service provisioning process.

4.3.1. Energy consumption

The total energy consumption \( E_{\text{ind}} \) for the download of a single file when the mobile operator uses the individual approach for mobile telecom service provisioning can be calculated as follows:

\[
E_{\text{ind}} = nE_{\text{bit(GPRS/UMTS)}}S_{\text{file}}
\]

where \( n \) is the number of users in the system, \( E_{\text{bit(GPRS/UMTS)}} \) denotes the energy consumption in Joules per bit needed for sending and receiving data via mobile network (i.e., GPRS or UMTS) and \( S_{\text{file}} \) denotes size of the downloaded file in Mb.

The total energy consumption \( E_{\text{col}} \) for the download of a single file, when the mobile operator uses the collaborative approach, consists of the energy
consumption from both phases of the SOMA and can be calculated as follows:

\[
E_{col} = \frac{E_{\text{bit}(\text{GPRS/UMTS})}S_{\text{file}}}{2(n-1)}E_{\text{bit}(\text{BT/WiFi})}(S_{\text{file}} + S_{\text{gossip}}). \tag{14}
\]

In the equation (14), \(S_{\text{gossip}}\) denotes the size of a gossip message in Mb, while \(m\) denotes number of parts that the content is divided in. Gossip messages are all messages (i.e. bid, asks, results) exchanged in one SOMA auction except the message for the exchange of the auctioned content part. The \(E_{\text{bit}(\text{BT/WiFi})}\) denotes the energy consumption in Joules per bit needed for sending and receiving data when using short-range communication technology (i.e. Bluetooth or WiFi). By introducing substitutions \(\frac{E_{\text{bit}(\text{BT})}}{E_{\text{bit}(\text{GPRS})}} = \alpha\) and \(\frac{E_{\text{bit}(\text{WiFi})}}{E_{\text{bit}(\text{UMTS})}} = \beta\) in equation (14) we get:

\[
E_{col(\text{GPRS+BT})} = \frac{E_{\text{bit}(\text{GPRS})}S_{\text{file}}}{E_{\text{bit}(\text{GPRS})}S_{\text{file}}(1 + 2\alpha(n-1)(1 + m\frac{S_{\text{gossip}}}{S_{\text{file}}}))},
\]

and

\[
E_{col(\text{UMTS+WiFi})} = \frac{E_{\text{bit}(\text{UMTS})}S_{\text{file}}}{E_{\text{bit}(\text{UMTS})}S_{\text{file}}(1 + 2\beta(n-1)(1 + m\frac{S_{\text{gossip}}}{S_{\text{file}}}))}.
\tag{15}
\]

The \(E_{col(\text{GPRS+BT})}\) denotes the total energy consumption in a scenario of the Collaborative Downloading service when mobile users’ devices support GPRS and Bluetooth networking technologies, while \(E_{col(\text{UMTS+WiFi})}\) denotes the total energy consumption in a scenario of the Collaborative Downloading service when mobile users’ devices support UMTS and WiFi networking technologies.

Furthermore, by introducing an approximation\(^{10}\) \((S_{\text{gossip}}/S_{\text{file}} \to 0)\) we can simplify expressions given in equations (15) and (16) as follows:

\[
E_{col(\text{GPRS+BT})} \approx nE_{\text{bit}(\text{GPRS})}S_{\text{file}}\left(\frac{1 - 2\alpha}{n} + 2\alpha\right), \tag{17}
\]

and

\[
E_{col(\text{UMTS+WiFi})} \approx nE_{\text{bit}(\text{UMTS})}S_{\text{file}}\left(\frac{1 - 2\beta}{n} + 2\beta\right), \tag{18}
\]

\(^{10}\)When exchanging multimedia content the \(S_{\text{gossip}}/S_{\text{file}}\) ratio is mainly smaller than 1/1000 so we do not take it into account.
Finally, by using, equations (13), (17) and (18) and the data from Table 1 we determine the decrease of total energy consumption for groups consisting of $n \in [2, 6]$ users. The results are as follows:

$$E_{col(GPRS+BT)} \approx \begin{cases} 0.54 \cdot E_{ind(GPRS)}, \text{ when } n = 2 \\ 0.39 \cdot E_{ind(GPRS)}, \text{ when } n = 3 \\ 0.32 \cdot E_{ind(GPRS)}, \text{ when } n = 4 \\ 0.27 \cdot E_{ind(GPRS)}, \text{ when } n = 5 \\ 0.24 \cdot E_{ind(GPRS)}, \text{ when } n = 6 \\ 
\end{cases}$$ (19)

and

$$E_{col(UMTS+WiFi)} \approx \begin{cases} 0.89 \cdot E_{ind(UMTS)}, \text{ when } n = 2 \\ 0.85 \cdot E_{ind(UMTS)}, \text{ when } n = 3 \\ 0.83 \cdot E_{ind(UMTS)}, \text{ when } n = 4 \\ 0.82 \cdot E_{ind(UMTS)}, \text{ when } n = 5 \\ 0.81 \cdot E_{ind(UMTS)}, \text{ when } n = 6 \\ 
\end{cases}$$ (20)

4.4. Time consumption

The total time consumption $T_{ind}$ for the download of a single file when the mobile operator uses the individual approach for mobile telecom service provisioning can be calculated as:

$$T_{ind} = \frac{n S_{file}}{v(GPRS/UMTS)}$$ (21)

where $v(GPRS/UMTS)$ denotes the effective transmission speed while users are sending and receiving data via mobile network (i.e. GPRS or UMTS).

On the other hand, the total time consumption $T_{col}$ for the download of a single file when the mobile operator uses the collaborative approach, for mobile telecom service provisioning can be calculated as:

$$T_{col} = \frac{S_{file}}{v(GPRS/UMTS)} + \frac{(n - 1)(S_{file} + m S_{gossip})}{v(BT/WiFi)}$$ (22)

where $v(GPRS/UMTS)$ denotes the effective transmission speed while users are sending and receiving data when using short-range communication technology (i.e. Bluetooth or WiFi).

By introducing substitutions $v_{BT}/v_{GPRS} = \gamma$ and $v_{WiFi}/v_{UMTS} = \delta$ in equation (22) we get:

$$T_{col(GPRS+BT)} = \frac{S_{file}}{v(GPRS)} + \frac{(n - 1)(S_{file} + m S_{gossip})}{v(GPRS)} = \frac{S_{file}}{v(GPRS)} \left(1 + \frac{1}{\gamma(n - 1)(1 + m \frac{S_{gossip}}{S_{file}})}\right),$$ (23)
and
\[
T_{\text{col}}(\text{UMTS+WiFi}) = \frac{S_{\text{file}}}{v_{\text{UMTS}}} + \frac{(n-1)(S_{\text{file}}+mS_{\text{gossip}})}{v_{\text{UMTS}}(1 + \frac{1}{3}(n-1)(1 + mS_{\text{gossip}}/S_{\text{file}}))},
\]

Equation (24)

The \(T_{\text{col}}(\text{GPRS+BT})\) denotes the total time consumption in a scenario of the Collaborative Downloading service when mobile users’ devices support GPRS and Bluetooth networking technologies, while \(T_{\text{col}}(\text{UMTS+WiFi})\) denotes the time consumption in a scenario of the Collaborative Downloading service when mobile users’ devices support UMTS and WiFi networking technologies.

Again, by introducing an approximation \((S_{\text{gossip}}/S_{\text{file}} \rightarrow 0)\) in equations (23) and (24) and using them together with equation (21) and the data from Table 1, we determine the decrease of the total time consumption for groups consisting of \(n \in [2,6]\) users. The results are as follows:

\[
T_{\text{col}}(\text{GPRS+BT}) \approx \begin{cases} 
1.41 \times T_{\text{ind}}(\text{GPRS}), & \text{when } n = 2 \\
1.55 \times T_{\text{ind}}(\text{GPRS}), & \text{when } n = 3 \\
1.61 \times T_{\text{ind}}(\text{GPRS}), & \text{when } n = 4 \\
1.65 \times T_{\text{ind}}(\text{GPRS}), & \text{when } n = 5 \\
1.68 \times T_{\text{ind}}(\text{GPRS}), & \text{when } n = 6 
\end{cases}
\]

Equation (25)

and

\[
T_{\text{col}}(\text{UMTS+WiFi}) \approx \begin{cases} 
0.54 \times T_{\text{ind}}(\text{UMTS}), & \text{when } n = 2 \\
0.39 \times T_{\text{ind}}(\text{UMTS}), & \text{when } n = 3 \\
0.31 \times T_{\text{ind}}(\text{UMTS}), & \text{when } n = 4 \\
0.26 \times T_{\text{ind}}(\text{UMTS}), & \text{when } n = 5 \\
0.23 \times T_{\text{ind}}(\text{UMTS}), & \text{when } n = 6 
\end{cases}
\]

Equation (26)

4.5. Analytical model results discussion

The results from equations (19) and (20) are shown in Fig. 7a and they present energy consumption savings for the two proposed scenarios of the Collaborative Downloading service (i.e. \((1 - E_{\text{col}}(\text{GPRS+BT})/E_{\text{ind}}(\text{GPRS}))\)) for the first scenario when mobile users’ devices support GPRS and Bluetooth networking technologies and \((1 - E_{\text{col}}(\text{UMTS+WiFi})/E_{\text{col}}(\text{UMTS}))\) for the second scenario when mobile users’ devices support UMTS and WiFi networking technologies. Analogously, the results from equations (25) and (26) are shown in Fig. 7b and they present time consumption savings for the two proposed scenarios of the Collaborative Downloading service (i.e. \((1 - T_{\text{col}}(\text{GPRS+BT})/T_{\text{ind}}(\text{GPRS}))\)) for the first scenario and \((1 - T_{\text{col}}(\text{UMTS+WiFi})/T_{\text{ind}}(\text{UMTS}))\) for the second scenario.
for the second scenario). Both energy and time efficiency are calculated by comparing the results of the proposed scenarios of the Collaborative Downloading service (i.e. collaborative approach) with the results of the current practice in the mobile data download (i.e. individual approach).

From Fig. 7a we can see that the first scenario (i.e. GPRS+BT) saves more energy than the second scenario (i.e. UMTS+WiFi), with the ratios varying from 46% vs. 11% for the two-user-group to 76% vs. 19% for the six-user-group, and therefore, the first scenario is more environmentally friendly. However, a drawback of the first scenario emerges from the fact that the ratio of effective transmission speeds $v_{(BT)}/v_{(GPRS)}$ is much smaller than the ratio $v_{(WiFi)}/v_{(UMTS)}$ (see Table 1). This is why, as shown in Fig. 7b), the collaborative approach in the first scenario (i.e. GPRS+BT) lasts between 41% (for the two-user-group) and 68% (for the six-user-group) longer than the individual approach in that same scenario. On the other hand, the collaborative approach in the second scenario (i.e. UMTS+WiFi) does not only save energy of user devices but also saves between 46% (for the two-user-scenario) and 77% (for the six-user-scenario) of users’ time when compared with the individual approach in that same scenario.

5. Conclusion and Future Work

In this paper we presented the Collaborative Downloading, a proof-of-concept swarm-oriented mobile telecom service based on the Telco 2.0 service provisioning practices. Current practices in telecom service provisioning are
based on an individual approach towards mobile users and do not take into account energy efficiency of user devices. On the other hand, our proposal – the Collaborative Downloading service – is implemented by using multi-agent technology and it combines swarm intelligence and market-based mechanisms in order to enable serendipitous collaboration among mobile users, as well as significant energy savings on their user devices. The fact that the mentioned benefits fully comply with the idea of sustainable communication allows us to envision our proof-of-concept service as a step towards green communication.

For future work we plan to implement the two proposed scenarios of the Collaborative Downloading service. First we will implement a scenario where mobile users’ devices support GPRS and Bluetooth networking technologies and, afterwards, a scenario where mobile users’ devices support UMTS and WiFi networking technologies.

Acknowledgements

This work was carried out within research projects 036-0362027-1639 "Content Delivery and Mobility of Users and Services in New Generation Networks", supported by the Ministry of Science, Education and Sports of the Republic of Croatia.

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