Application-Layer Community-Oriented Uplink Scheduler for CDMA Networks

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Abstract – This paper focuses on community-based mobile applications and delivers an efficient application-layer uplink scheduler for the collection of community responses in CDMA networks, capable of pursuing the best possible compromise between delay and radio resource constraints. The scheduling problem is mathematically formulated and solved, based on a novel probabilistic approach inspired by the birthday paradox. Results of the proposed approach are presented and analyzed.

Keywords – CDMA, mobile community applications, uplink load factor, upload scheduling

1. Introduction

Community-based mobile applications are expected to grab significant market share, in the years to come. This trend is firstly foreseen as a natural evolution of existing Web-oriented counterparts, such as Facebook [1], MySpace [2], etc. Additionally, however, a community of mobile users may be perceived not only as a social network but also as a *highly distributed sensor network* that may be exploited to properly "sniff" its RF or physical environment [3]-[5]. We may refer to the first group of mobile community applications as "*social network applications*", whereas to the second one as "*sensor-like applications*".

The main notion behind this second group of applications is the ability to issue a query for impersonalized information that resides in a community of mobile terminals. This information may vary both in size and nature. It may range from a few hundred bytes to a few MB. It may include various terminal-monitored parameters, such as: the perceived signal strength level of the base station or access point the terminal is attached to; the terminal velocity (retrievable through

GPS); the temperature or humidity levels in the terminal's area (future terminals are envisaged to be equipped with multi-purpose digital sensors); various layer-2, layer-3 and layer-4 historical measurements of the terminal operation; multimedia files, such as images, songs, videos, or text; and others.

As illustrated in Figure 1, these sensor-like mobile community applications involve the simultaneous response of multiple mobile terminals belonging to a specific community. This response process must satisfy two fundamental yet contradictory requirements:

(a) service delivery must be completed within acceptable time limits, leading to a strict constraint regarding the total available time for gathering all the community's responses

(b) minimum impact on the radio resources, meaning that there should be enough radio resources available to serve normal traffic

In CDMA networks, the aforementioned response process raises an even more important engineering challenge, since simultaneous upload transmissions increase intra-cell interference and raise the uplink load factor. The objective of this paper is to deliver an efficient application-layer uplink scheduler for community responses in CDMA networks, capable of pursuing the best compromise between the two aforementioned requirements. The solution to the problem at hand is based upon a novel probabilistic approach inspired by the birthday paradox [6]-[10]. To the authors' best knowledge, such an approach has never before been adopted or pursued for the problem at hand.

2. Background and Problem Formulation

2.1. Background

In the following, we concentrate on a UMTS cell that has n_u community users, $u_1, u_2, \ldots, u_{nu} \in U$, where $|U| = n_u$. Without loss of generality, we assume that each user has approximately the same amount of information to upload. Each user selects independently and randomly a single interval $s_1, s_2, \ldots, s_{ns} \in S$ to transmit in, where $|S| = n_s$.

The approach of randomly selecting an interval for transmission, in a totally distributed manner, is advantageous compared to a server-controlled scheduling (in which case the application server sequentially triggers a cell's community users, one after another). The reasons for this are listed below:

- the application server may have a rough but not exact estimation of the number of community members in the cell
- the complexity of triggering a group of members altogether, rather than one after another, is far lesser
- excessive overhead on the downlink (i.e., for triggering the terminals to respond back) is avoided through the use of the broadcast channel, instead of point to point messages

The maximum number of intervals to choose from, n_s, may be included within the broadcast message, along with the type of requested information.

Simultaneous transmissions are mostly undesirable in the uploading process, since they raise the uplink load factor, *ulf*, which is determined as follows, for a UMTS cell [11]-[12]:

$$ulf = (1+r)\cdot\sum_{j=1}^{N}\frac{1}{1+\dfrac{w}{\left(E_b/N_o\right)_j\cdot R_j\cdot x_j}} \tag{1}$$

where: **N**: total number of active users; **w**: chip rate (3.84Mcps); $\mathbf{x_j}$: activity factor of user j (x_j=1 for data, 0.67 for voice); $\mathbf{R_j}$: bit rate of user j; **r**: other to own cell interference ratio (r=0.55 for omni antennas, 0.65 for sector antennas); $\mathbf{(E_b/N_o)_j}$: e.g., 1.5dB for 144kbps packet data. Associated with the uplink load factor is the noise rise in the cell, defined as follows (in dB):

$$Noise\ Rise = -10\cdot\log\left(1-ulf\right) \tag{2}$$

Note that when the uplink load factor becomes close to 100%, the corresponding noise rise approaches infinity and the system reaches its pole capacity. This yields a limitation in the number of users that may be concurrently active in a CDMA cell, leading in our case to a limitation in the number of simultaneous community user transmissions. However, fewer simultaneous transmissions signify a larger delay in the collection of the entire set of community responses.

2.2. Problem Formulation

Since simultaneous community-user transmissions are undesirable, they can be treated as collisions and modeled according to a generalization of the birthday paradox. Let $H: U \rightarrow S$ be a hash function, where the set *U* of community users is the domain and the set S of intervals is the range. If $H(u_i) = s_j$, it means that user $u_i \in U$ chooses to transmit in the interval $s_j \in S$. A collision for H is a distinct pair u_i, $u_j \in U$, $i \neq j$, such that $H(u_i) = H(u_j)$. Multi-collisions are also an important notion and are defined similarly. A k-collision ($k \in \mathbb{N}$) for H exists if there is a set $V \subseteq U$ such that $V = \{u_i \mid H(u_i) = s\}$, $s \in S$, $1 \leq i \leq n_u$, and $|V| = k$.

According to (1), if n community users transmit concurrently, the uplink load factor that they cause is (the activity factor is set equal to 1):

$$ulf_{com}(n) = \frac{n \cdot (1+r)}{1 + \dfrac{w}{\left(E_b / N_o\right) \cdot R}} \tag{3}$$

The sum of the uplink load factor caused by the community and the uplink load factor due to normal use must be restrained below 100%, leading to a constraint A_{ULFcom} for ulf_{com} well below 100% (e.g., A_{ULFcom} = 30%):

$$ulf_{com}(n) \leq A_{ULFcom} \tag{4}$$

The requirement represented by (4) may be relaxed by introducing a probabilistic approach, according to which ulf_{com} must not exceed A_{ULFcom} with a probability more than A_P, where $A_P \in [0,1]$:

$$P\left[ulf_{com}\left(\left|H^{-1}(s)\right|\right) \geq A_{ULFcom}\right] \leq A_P,\ s \in S \tag{5}$$

Equivalently, requirement (5) may be expressed as follows:

$$P\left[\left|H^{-1}(s)\right| \geq k\right] \leq A_P,\ s \in S, \text{ with } k \in \mathbb{N} \text{ such that}$$

$$k = \min(\ell) : ulf_{com}\left(\left|H^{-1}(\ell)\right|\right) > A_{ULFcom},\ \ell \in \mathbb{N} \tag{6}$$

In parallel, the entire uploading process is time constrained, since the collection of all the community members' responses must be done as fast as possible. This leads to an additional requirement, according to which the maximum total delay must not surpass a time limit A_T: $n_s \cdot T \leq A_T$ (7)

where $n_s = |S|$, and T is the time duration of a transmission interval, i.e.:

$$T = \frac{\langle \text{msg length} \rangle}{\langle \text{data rate} \rangle} + \langle \text{guard time} \rangle \tag{8}$$

By defining threshold A_S as follows: $A_S = \left\lceil \frac{A_T}{T} \right\rceil$ (9)

requirement (7) may be rewritten in a simpler form:

$$n_s \leq A_S,\ A_S \in \mathbb{N} \tag{10}$$

Since each user selects an interval independently and randomly, the probability of relation (6) becomes a function of the number of intervals n_s, the number of community users n_u, as well as of k, i.e.:

$$P\left[\left|H^{-1}(s)\right| \geq k\right] = p\left(n_s, n_u, k\right) \quad (11)$$

Assuming that the number of community users, n_u, in a cell is given, we seek the minimum n_s that satisfies both requirements (6) and (10). In other words, the problem is formulated as follows: What is the minimum number of time intervals (value of n_s) which guarantees: *(i)* that the uplink load factor will not exceed a given limit with a probability greater than a predefined threshold; and *(ii)* that the total duration of the uploading process will not exceed a time constraint.

3. Problem Solution and Results

3.1. Problem Solution

In order to solve the problem formulated above, we may note that the probability of relation (6) expresses the probability that at least k community users coincide (select the same interval), which triggers as to resort to the birthday paradox problem. Consequently, the probability in question is given by [6]-[10]:

$$p\left(n_s, n_u, k\right) = 1 - \sum_{j=1}^{k-1} Q\left(n_s, n_u, j\right) \quad (12)$$

where the following recursive definition is employed:

$$Q\left(n_s, n_u, \ell\right) = \begin{cases} 0, \ \textit{if} \ \left(n_u < \ell\right) \ \textit{or} \ \left(n_s < 1\right) \\ \textit{otherwise}: \\ \begin{cases} \left[\prod_{i=0}^{n_u - 1} 1 - \dfrac{i}{n_s}\right], \ \textit{if} \ \ell = 1 \\ \textit{otherwise}: \\ \sum_{i=1}^{\left\lfloor \frac{n_u}{\ell} \right\rfloor} q\left(n_s, n_u, \ell, i\right) \cdot A\left(n_s, n_u, \ell, i\right) \end{cases} \end{cases} \quad (13)$$

where:

$$q\left(n_s, n_u, \ell, i\right) = \left(1 - \frac{i}{n_s}\right)^{n_u - \ell \cdot i} \cdot \prod_{j=1}^{\ell \cdot i} \frac{n_u - j + 1}{n_s} \cdot \prod_{j=1}^{i} \frac{n_s - j + 1}{j \cdot \ell!} \quad (14)$$

$$A(n_s, n_u, \ell, i) = \begin{cases} \sum_{j=1}^{\ell-1} Q(n_s - i, n_u - \ell \cdot i, j), & if\ \ell \cdot i < n_u \\ 1, & otherwise \end{cases} \quad (15)$$

In particular, function $Q(n_s, n_u, j)$ denotes the probability that an interval is shared by exactly j (and no more) community users out of a group of n_u community users. Then, the probability that an interval is shared by k or more people is given by (12).

3.2. Results

We examine a scenario with the following parameter values: $\mathbf{n_u}$**:** 10, 20, …, 100 community users; $\mathbf{n_s}$**:** 1, 2, …, 200 intervals; **r**=0.65; **w**=3.84Mcps; **R**=144kbps; $\mathbf{E_b/N_o}$=1.5dB; $\mathbf{A_{ULFcom}}$**:** 20%, 30%, 40%; $\mathbf{A_P}$=0.5; $\mathbf{A_S} \in [1, 200]$.

Results are summarized in Figure 2(a)-(c), for different values of the A_{ULFcom} threshold. Since A_P=0.5, acceptable are only the solutions below the corresponding plane. As a representative example, we indicate the solutions for the case of n_u=40 community users. We denote as "*safest*" the acceptable n_s value that corresponds to the minimum possible probability of exceeding the A_{ULFcom} threshold, whereas as "*fastest*" the one that corresponds to the minimum possible total delay. The intersection of surface $p(n_s,n_u,k)$ and plane n_u=40, extending from the "safest" up to the "fastest" solution point is the path of acceptable solutions, each one offering a unique trade-off between response collection speed and impact on the radio resources. We may also note from Figure 2 that the more relaxed (i.e., the greater) the A_{ULFcom} limit is, the smaller the value of n_s (thus, the total delay) has to be.

In summary, the following results can be derived from Figure 2:

1. For A_{ULFcom}=20% (Figure 2a),
   - safest solution: n_s = 200, resulting in $p(n_s=200,n_u=40,k) \approx 19.7\%$
   - fastest solution: n_s = 106, resulting in $p(n_s=106,n_u=40,k)=50\%$
   - generic solution: $n_s \in [106, 200]$
2. For A_{ULFcom}=30% (Figure 2b),
   - safest solution: n_s = 111, resulting in $p(n_s=111,n_u=40,k) \approx 5\%$
   - fastest solution: n_s = 51, resulting in $p(n_s=51,n_u=40,k)=50\%$
   - generic solution: $n_s \in [51, 111]$
3. For A_{ULFcom}=40% (Figure 2c),

- safest solution: n_s = 56, resulting in $p(n_s=56,n_u=40,k) \approx 4\%$
- fastest solution: n_s = 26, resulting in $p(n_s=26,n_u=40,k)=50\%$
- generic solution: $n_s \in [26, 56]$

4. Conclusion

In this paper, we presented an efficient application-layer uplink scheduler for community responses in CDMA networks, capable of pursuing the best compromise between the minimum possible total delay and the minimum possible impact on radio resources. The scheduling problem was mathematically formulated and solved, based on a novel probabilistic approach inspired by the birthday paradox. Results of this approach were presented and analyzed.

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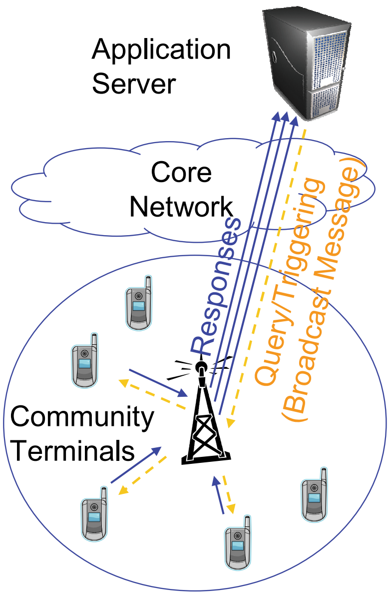

Figure 1. The concept of sensor-like mobile community applications

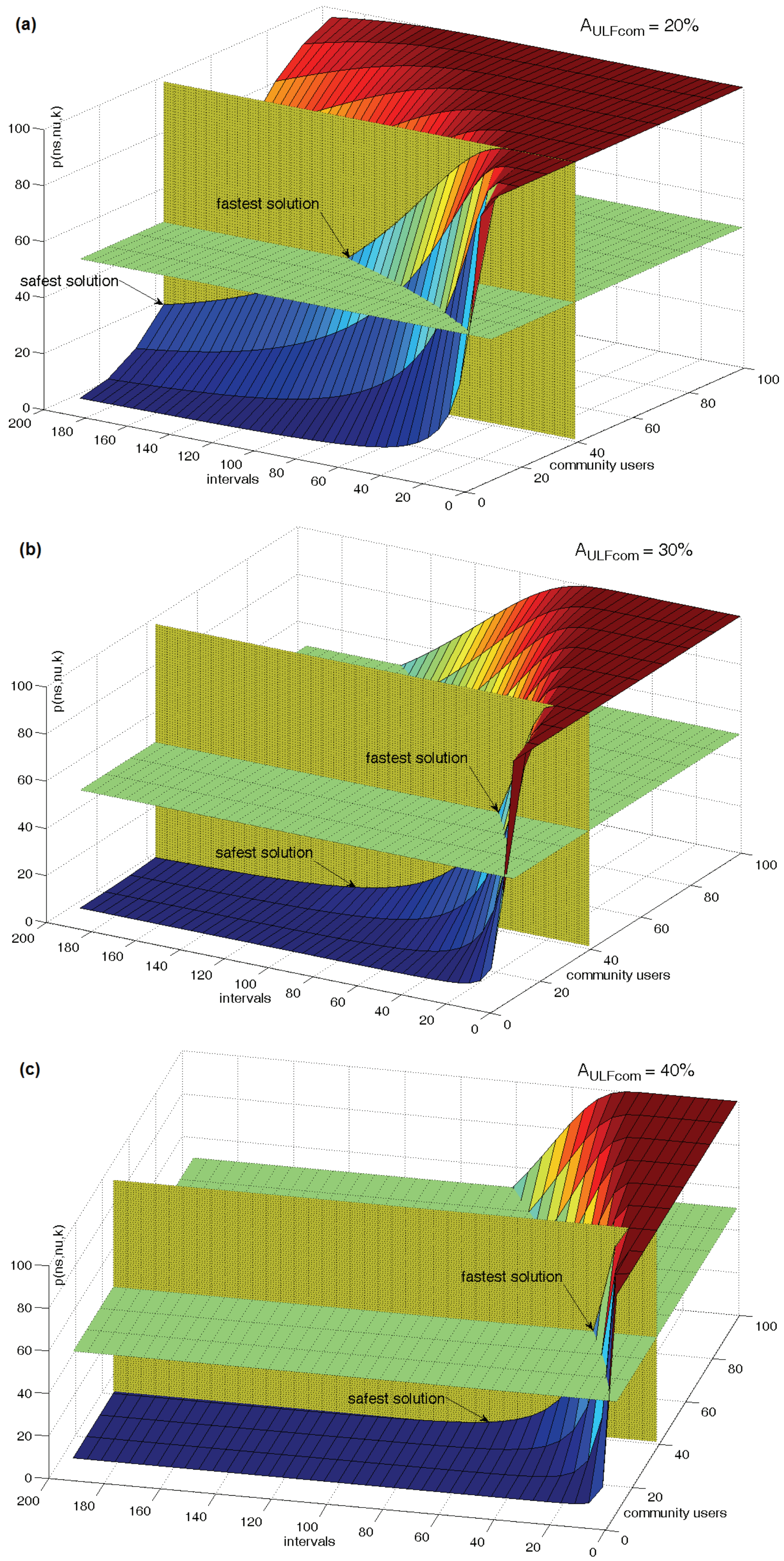

Figure 2. Results of the proposed method for A_{ULFcom} = 20%, 30%, 40%