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Performance optimization of an adaptive wireless push system in environments with locality of demand

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Abstract

In many data broadcasting applications clients are grouped into several groups, each one located at a different region, with the members of each group having similar demands. This paper proposes a mechanism that exploits locality of demand in order to increase the performance of wireless data dissemination systems. It trades the received energy per bit redundancy at distances smaller than the radius of the service area for an increased bit rate and thus increased transmission speed for items demanded by clients at such distances. The paper focuses on performance optimization of clients located around the geographical area of interest. It does so by protecting degradation caused by clients that are located elsewhere and demand the same information items with clients inside that area. Simulation results are presented that reveal significant performance improvement for clients located around the area of interest.

Keywords: Adaptive data broadcasting; Learning Automata; Locality of demand; Variable bit rate

1. Introduction

Data broadcasting has emerged as an efficient means for the dissemination of information over asymmetric wireless networks [1]. Examples of data broadcasting applications are traffic information, weather information, and news distribution systems. In such applications, client needs for data items are usually overlapping. Consequently, broadcasting stands to be an efficient solution, as the broadcast of a single information item will likely satisfy a (possibly large) number of client requests. A possible example of this case could be the case of traffic information systems. It is logical to assume that users demand traffic information regarding the area around their current position.

In a wireless data dissemination system, the transmission power of the broadcast server determines the service area. Thus, if one wants to provide data dissemination services in an area of radius R, transmission power must be set at such a level that guarantees the necessary energy per bit to noise density per Hz (E_b/N_0) ratio for clients located at the border of the service area. However, in wireless cellular environments the path loss of wireless signals is a $1/d^n$ type loss with a typical $n \geqslant 4$ [9]. This fact creates an increasing redundancy in the E_b/N_0 figure for clients at distances $d < R$ from the antenna.

This paper proposes a mechanism that exploits locality of demand in order to increase the performance of wireless data dissemination systems. Locality of demand means that clients are grouped into groups each one located at a different place. Additionally, members of each group have similar demands different from those of clients at other groups. The proposed approach can trade the E_b/N_0 redundancy at clients in groups at distances $d < R$ for an increased bit rate for the broadcast of the items demanded

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by these groups. Knowledge of client positions is conveyed to the server via a simple feedback pulse from the clients, a mechanism that was used in [6] in order to provide adaptivity to dynamic client demands. Additionally, a simple mechanism is introduced that protects performance around the geographical area of interest from degradation caused by clients that are located elsewhere and demand the same information items with clients inside that area.

The remainder of this paper is organized as follows: Section 2 presents the proposed system. Simulation results which reveal the performance superiority of the proposed approach to that of the fixed rate adaptive wireless push scheme of [6] and the variable rate on of [7] in environments with locality of demand are presented in Section 3. Finally, Section 4 summarizes and concludes the paper.

2. The variable bit rate adaptive wireless push system with regional performance improvement

2.1. The Learning Automaton-based broadcast server

Learning Automata [10–13] are structures that can acquire knowledge regarding the behavior of the environment in which they operate. In the area of data networking Learning Automata have been applied to several problems, including the design of self-adaptive MAC protocols [14–17].

In the fixed rate adaptive wireless push system [6], which enhanced the non-adaptive one of [4], the server is equipped with an *S*-model Learning Automaton that contains the server's estimate p_i of the demand probability d_i for each data item i among the set of the items the server broadcasts. Clearly, $\sum_{i=1}^{N} d_i = 1$, where N is the number of items in the server's database. At each cycle, the server selects to transmit the item i that maximizes the cost function $G(i) = (T - R(i))^2 \frac{d_i}{l_i}\left(\frac{1+E(l_i)}{1-E(l_i)}\right)$, $1 \leqslant i \leqslant N$, where T is the current time, $R(i)$ the time when item i was last broadcast, l_i is the length of item i and $E(l_i)$ is the probability that an item of length l_i is erroneously received. For items that have not been previously broadcast, $R(i)$ is initialized to -1. If the maximum value of $G(i)$ is shared by more than one item, the algorithm selects one of them arbitrarily. Upon the broadcast of item i at time T, $R(i)$ is changed so that $R(i) = T$.

After the transmission of item i, the broadcast server awaits for an acknowledging pulse from every client that was waiting item i. The aggregate received pulse power is used at the server to update the Automaton. The probability distribution vector p maintained by the Automaton estimates the demand probability d_i (and thus the popularity) of each information item i. For the next broadcast, the server chooses which item to transmit by using the updated vector p.

When the transmission of an item i does not satisfy any waiting client, the probabilities of the items do not change. However, following a transmission that satisfies clients, the probability of item i is increased. The following Liner Reward-Inaction ($L_{\text{R-I}}$) probability updating scheme [11] is employed after the transmission of item i (assuming it is the server's kth transmission).

$$\begin{aligned} p_j(k+1) &= p_j(k) - L(1-b(k))(p_j(k)-a), \forall j \neq i, \\ p_i(k+1) &= p_i(k) + L(1-b(k)) \sum_{i \neq j} (p_j(k)-a), \end{aligned} \qquad (1)$$

where $p_i(k) \in (a, 1)$ $\forall k$ and $L, a \in (0, 1)$. Parameter a prevents the probabilities of non-popular items from taking values in the neighborhood of zero and thus increases the adaptivity of the Automaton. $b(k)$ is the environmental response and is represented by the sum of the received feedback pulses after the server's kth transmission. After normalization the value of $b(k)$ lies in the interval $[0, 1]$.

The normalization procedure needs a mechanism that will enable the server to possess an estimate of the number of clients under its coverage. This is achieved by the broadcasting of a control packet that notifies all clients in the service area of the antenna to respond with a feedback pulse. The server will use this aggregate received pulse to estimate how many clients are within its coverage area. However, as the signal strength of each client's pulse at the server suffers a $1/d^n$ type path loss (with a typical $n = 4$ [9]), the feedback pulses of clients must be power controlled. To this end, every information item will be broadcast including information regarding the signal strength used for its transmission and acknowledging clients set the power of their feedback pulse to be the inverse of the ratio (signal strength of the received item)/(signal strength of the item transmission). Using this form of power control, the contribution of each client's feedback pulse at the server will be the same regardless of the client's distance from the antenna.

Using the described scheme, the item probabilities estimated by the automaton converge to the actual demand probabilities for each information item. Via simulation, this convergence is shown in Fig. 1 for a randomly selected information item. Overall client demand for the item is

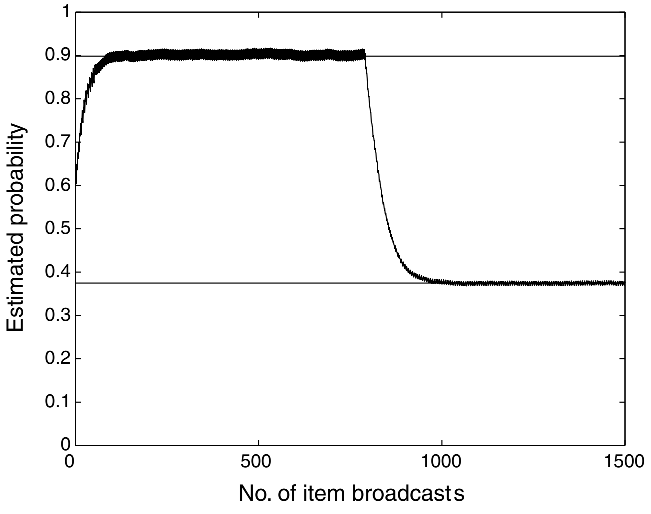

Fig. 1. Convergence of automaton estimation of the demand of an item.

initially unknown to the server. It can also be seen that they are of a dynamic nature as well: at some time instant, the initial overall demand probability for the selected item (solid line) changes to a new one (dashed line). It is clearly seen, that convergence of the item probability estimated by the automaton to the overall client demand for this item is achieved. Moreover, simulation results in [6] and [18] have demonstrated efficient operation in environments characterized by dynamic and a-priori unknown to the server, client demands.

2.2. The bit rate variation mechanism

To the authors' knowledge, locality of demand has not been taken into account in related research; on the contrary, clients are assumed to be uniformly distributed inside the service area and generally make item requests using the same or similar patterns (e.g. [4,6]). In many cases however, clients are grouped into several groups located at different places with the clients of each group having similar demands, different from those of clients at other groups.

The method proposed in [7] aims in taking advantage of locality of demand. It does so by acknowledging that in a typical data broadcasting application (and generally in wireless cellular systems), service area is an area of certain radius R inside which mobile clients are able to receive information items while experiencing a Bit Error Rate (BER) below or equal to a certain requirement value. The size of the service area depends on a number of parameters, such as the type of modulation that is used, the bit rate, the server's transmission power and noise density per Hz and is determined by a simple rule stating that its border is where the received energy per bit E_b divided by the noise density per Hz N_0 equals a certain constant A. The value of A is determined so that the E_b/N_0 ratio results to a BER below or equal to a set requirement. Thus at the border of the service area it stands that:

$$\frac{E_b}{N_0} = A \Rightarrow E_b = A', \tag{2}$$

where $A' = AN_0$.

Since $E_b = T_b S_R$, where S_R is the received power at distance R from the antenna and T_b is the bit duration, we can rewrite the above relation as:

$$T_b S_R = A'. \tag{3}$$

Finally, since in wireless cellular environments the path loss of wireless signals at distance d is a $1/d^n$ type loss (with a typical value of $n \geqslant 4$), (3) can be expressed as:

$$R^{-n} T_b = A'. \tag{4}$$

In fixed bit rate systems, clients inside the service area (at distance $d < R$) experience even lower BERs than those required due to smaller distance from the antenna. Thus, for such clients it holds that $E_b > A'$ and therefore $d^{-n} T_b > A'$. Assume that there exists locality of demand, as defined earlier. Then we can exploit the above mentioned redundancy in the received BER by dynamically reducing the T_b parameter for each information item i so that it always holds that $d^{-n} T_b(d) = A'$, where d is the distance of the group of clients that access item i.

Based on the above reasoning, the adaptive system of [6] is enhanced by [7] as follows: each information item comprises a header that contains information that uniquely identifies the item. All item headers are always broadcast with the default T_b value, while the T_b value for the main item payload can be altered by the server. After the transmission of item i, the server waits for acknowledgment pulses from all mobile clients that were satisfied by this transmission. Since we consider groups of clients having the same interests, acknowledgment pulses for a certain item will be from a group of collocated clients and therefore arrive together at the server. The server monitors the time elapsed from the broadcast of item i until the aggregate pulse is received and uses this information to calculate the distance d of the group of clients from the antenna. When it broadcasts the next instance of this item the bit duration that will be used, $T_b(d)$, will be such that satisfies the requirement that $d^{-n} T_b(d) = A'$. Change of the bit duration is not a problem for the mobile client, as it can be informed of this via piggybacking of the new bit duration in the item header, which is always broadcast with the default T_b value.

As far as acknowledgment pulses are concerned, a client responds to the server via such a pulse if it demands item i and successfully receives i's header. We explain that this provides support for clients that may have broken away from the main group and are located further away from the antenna than the main group. Assume that such a client C, at a distance $d1$ receives only the header of i due to the fact that the main item payload has been transmitted with a bit rate determined by the location of the main group, which is closer to the antenna. In that case the server will receive more than one feedback pulses, one corresponding to the main group and one from C. In order to prevent C from starvation, the server will schedule the broadcast of the next instance of item i according to the feedback pulse of C (thus the client further away). This enables the client further away from the group to successfully receive item i when it is next broadcast. At the next broadcast of item i, C will successfully receive the item. However, this time C will not transmit a feedback pulse so as not to acknowledge twice reception of one instance of item i, a fact that would provide inaccurate information regarding demand for item i to the probability updating scheme.

2.3. Performance increase around the area of interest

However, the scheme of [7] with acknowledging clients located further away from the main group can cause significant performance degradation for the main group of clients. This is because acknowledging clients further away will raise the bit duration for the information items demanded by them (and also the main group) and consequently lower the average response time of clients in the main group. Therefore, a mechanism is needed in order to protect the increased performance around the geographical area of interest for a certain application (thus the performance of the main group) while also ensuring that clients further away are not subject to starvation. A simple and acceptable solution would be for the server to allow a client further away from the main group to define the bit duration for subsequent transmissions with a probability inversely proportional to the distance of the client from the main group. Thus, clients very far away from the main group whose feedback will greatly raise the bit duration will rarely be taken into account for determination of subsequent bit durations. On the other hand, clients close to the main group whose feedback will cause a smaller increase on bit duration will be taken into account for determination of subsequent bit durations more frequently. This is also logical from the point of view of the client further away: the less is its distance from the main group, the greater is its opportunity of receiving service. Simulation results in the next section show significant performance improvement for the main client groups.

3. Performance evaluation

In order to assess the performance increase offered by the proposed system (denoted by S_3 in the figures) in areas with locality of demand, we used simulation to compare it to the fixed bit rate system of [6] (denoted by S_1 in the figures) and that of [7] (denoted by S_2 in the figures). In S_2, the bit duration for the subsequent broadcast of an information item is always defined by the acknowledging client further away. The comparison is made in an environment characterized by client demands that are a-priori unknown to the server and location dependent.

3.1. Server model

We consider a broadcast server having a database of equally sized *Dbs* data items. The server is initially unaware of the demand for each item, so initially every item has a probability estimate p_i of $1/Dbs$. In the fixed bit rate system, the server broadcasts all items with the same bit rate. In the variable rate system however, the server determines the bit rate to use for each item according to the proposed scheme. Page lengths vary from $L_0 = 1$ to $L_1 = 10$ according to a random distribution where page lengths are random integers uniformly distributed in $[L_0..L_1]$.

3.2. Client model

We consider a client population of *ClNum* clients that have no cache memory, an assumption also made in other similar research (e.g. [4] and [6]). Clients are grouped into G groups each one of which is located at a different distance from the antenna and outside the antenna's near field. Any client belonging to group $g, 1 \leqslant g \leqslant G$ is interested in the same subset Sec_g of the server's database. All items outside this subset have a zero demand probability at the client. Finally, $Sec_i \neq Sec_j, \forall i,j \in [1..G], i \neq j$, which means that there do not exist common demands between any two clients belonging to different groups.

Assume that such a subset comprises *Num* pages. The demand probability d_i for each item in place i in that subset, is computed according to the Zipf distribution, which is used in other papers dealing with data broadcasting as well [2–8]:

$$d_i = c\left(\frac{1}{i}\right)^{\theta}, \quad \text{where } c = 1\Big/\sum_{k}\left(\frac{1}{k}\right)^{\theta}, \ k \in [1..Num], \tag{5}$$

where θ is a parameter named access skew coefficient. For $\theta = 0$, the Zipf distribution reduces to a uniform distribution of demand for the items in that range. For large values of θ, the Zipf distribution produces increasingly skewed demand patterns. The Zipf distribution can thus efficiently model applications that are characterized by a certain amount of commonality in client demands. For a database comprising 150 items, the demand probabilities per item for different values of θ in [1..150] are shown in Fig. 2.

Client placement takes place among *LP* different distance points outside the antenna's near field, with the maximum distance corresponding to the coverage radius of the system. Members of a group g are initially located at a distance Loc_g. To simulate some "noise" in client placement, we introduce the parameter *Dev*, which determines the percentage of clients that deviate from initial client placement. For every client, a coin toss, weighted by *Dev*, is made. If the outcome of the toss states that the client is to deviate from the initial client placement then its position is changed to a new one selected in a uniform manner from the interval [1..*LP*].

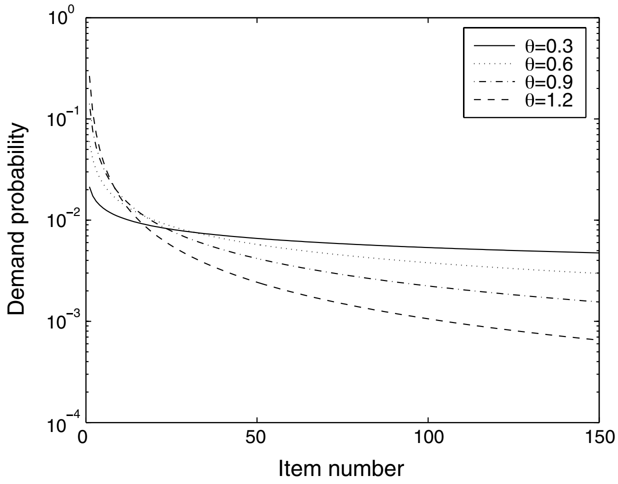

Fig. 2. Demand probability produced by the Zipf distribution for different values of θ.

3.3. The simulation environment

We performed our experiments with an event-driven simulator coded in C. The simulator models the *ClNum* mobile clients, the broadcast server and the server–client links as separate entities. We assume that the broadcast server's antenna is at the center of the circular cell and a path loss model of $1/d^n$. In order to model different group sizes, we also calculated the size of each group g via the above mentioned Zipf distribution governed by parameter θ_1.

Assume that any client located at distance d receives items with $E_b = Th$. In the fixed bit rate system every item being broadcast is assumed to be correctly decoded at the mobile clients. As was mentioned earlier, item headers are broadcast with the default bit rate and are thus assumed to be always correctly decoded by clients in the variable rate system as well. Item payloads however are correctly decoded by clients in the variable rate system if and only if they arrive at the demanding clients with an E_b figure being at least equal to Th.

The simulation is carried out until at least N item broadcasts have been made. Finally, the overhead due to the duration of the feedback pulse and the signal propagation delay is considered to be very small compared to the item transmission time (parameter Ovh), as would happen in low-speed broadcasting applications spanning an area of several kilometers.

3.4. Simulation results

The simulation results presented in this section were obtained with the following parameters values: $n = 4$, $Dbs = 150$, $ClNum = 10000$, $G = 5$, $Sec_1 = [0..59]$, $Sec_2 = [60.104]$, $Sec_3 = [105..119]$, $Sec_4 = [120..134]$, $Sec_5 = [135..149]$, $LP = 100$, $N = 10^6$, $Ovh = 10^{-3}$, $L = 0.15$, and $a = 10^{-4}$. Figs. 3–8 compare the performances offered by

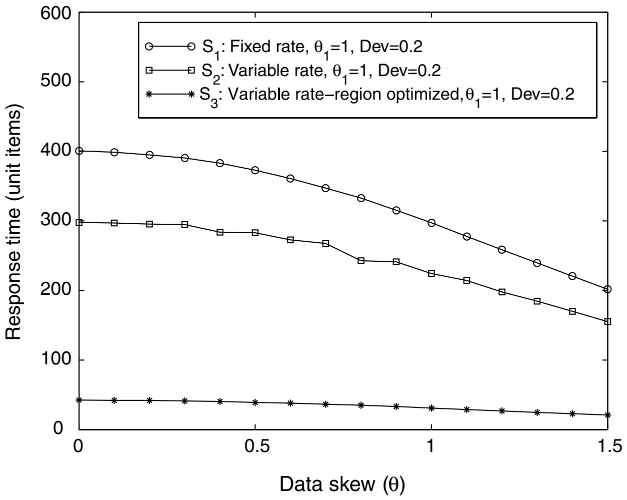

Fig. 3. Overall Mean Access Time for main group clients versus access skew coefficient θ in environment N_1. $\theta_1 = 1$.

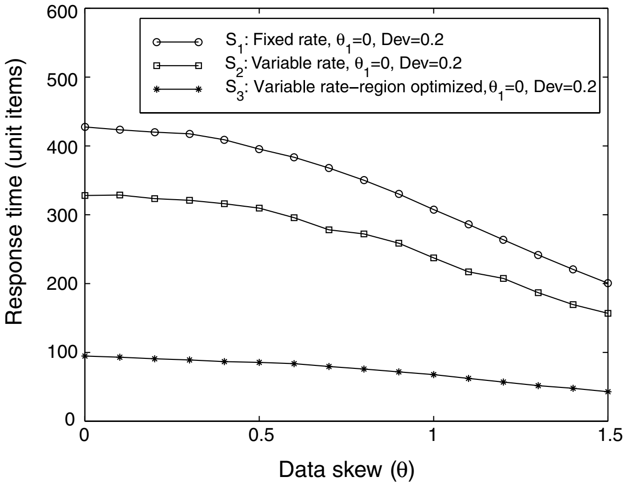

Fig. 4. Overall Mean Access Time for main group clients versus access skew coefficient θ in environment N_1. $\theta_1 = 0$.

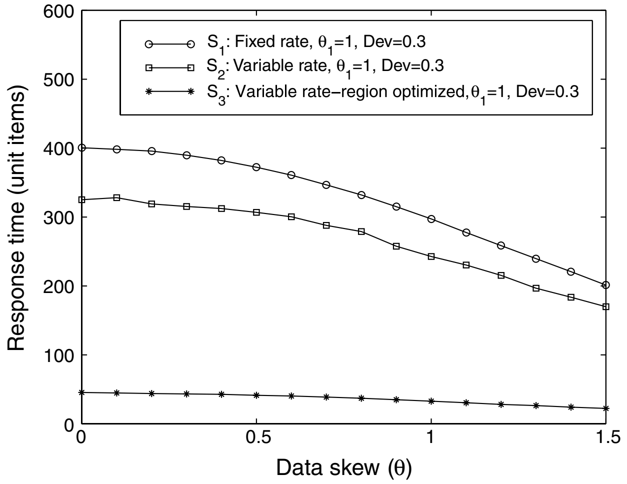

Fig. 5. Overall Mean Access Time for main group clients versus access skew coefficient θ in environment N_2. $\theta_1 = 1$.

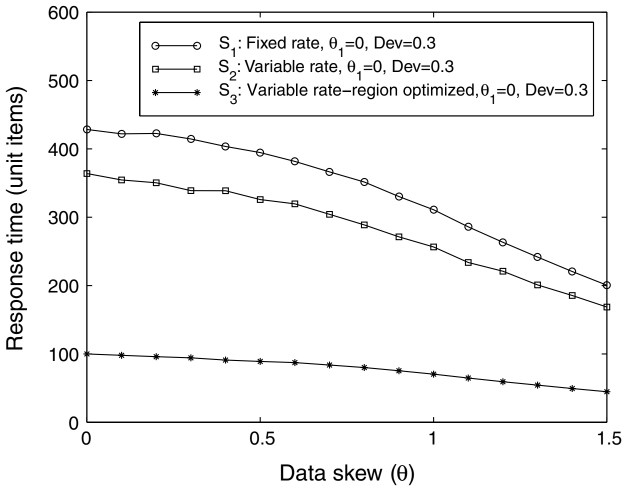

Fig. 6. Overall Mean Access Time for main group clients versus access skew coefficient θ in environment N_2. $\theta_1 = 0$.

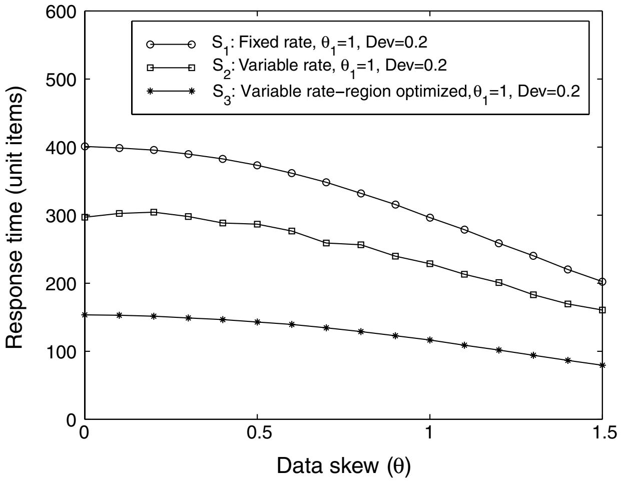

Fig. 7. Overall Mean Access Time for main group clients versus access skew coefficient θ in environment N_3. $\theta_1 = 1$.

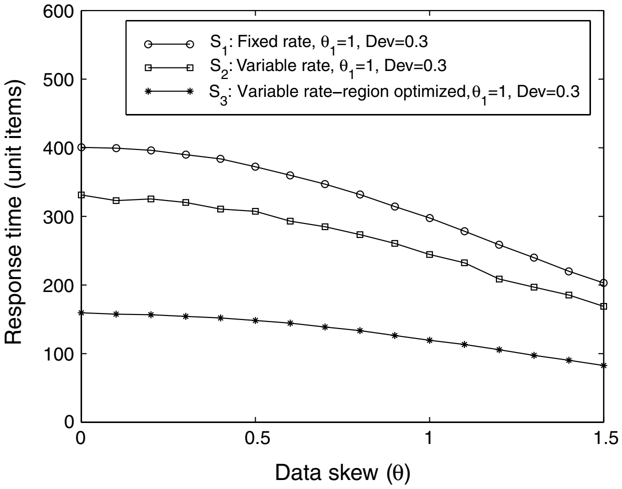

Fig. 8. Overall Mean Access Time for main group clients versus access skew coefficient θ in environment N_4. $\theta_1 = 1$.

the various schemes to client groups located around the area of interest of an application characterized by locality of demand (thus the mean performance among "main groups"). Unit of count is the duration for transmission of a unit length information item by the fixed rate system. Comparison is made in four different environments, N_1, N_2, N_3, and N_4. The parameters of these environments are:

(1) N_1: $Loc_1 = 10$, $Loc_2 = 30$, $Loc_3 = 50$, $Loc_4 = 70$, $Loc_5 = 90$, $Dev = 0.2$.
(2) N_2: $Loc_1 = 10$, $Loc_2 = 30$, $Loc_3 = 50$, $Loc_4 = 70$, $Loc_5 = 90$, $Dev = 0.3$.
(3) N_3: $Loc_1 = 90$, $Loc_2 = 70$, $Loc_3 = 50$, $Loc_4 = 30$, $Loc_5 = 10$, $Dev = 0.2$.
(4) N_4: $Loc_1 = 90$, $Loc_2 = 70$, $Loc_3 = 50$, $Loc_4 = 30$, $Loc_5 = 10$, $Dev = 0.3$.

The main conclusions that are drawn from the figures are:

- For all schemes (S_1, S_2, and S_3), the performances of clients around the area of interest improve for increasing values of the data skew parameter θ. This is expected behavior [6,18], as the Learning-Automaton adaptation mechanism manages to learn the actual demand probabilities of the various information items and use these values on the selection of the item to broadcast.
- The performances of clients around the area of interest of the adaptive variable bit rate systems (S_2 and S_3) are superior to that of the fixed bit rate one of [6] (S_1). This is due to the fact that in the adaptive system bit rate is not fixed but dynamically determined by client distance from the antenna; thus many items are transmitted much faster than in the fixed bit rate system resulting to the overall performance increase.
- The performance of the proposed adaptive variable rate system that optimizes response time for client groups located around the area of interest (scheme S_3) significantly outperforms the performances of the other schemes. This is due to the fact that the bit rate for groups located near the antenna is rarely affected by acknowledgments of clients further away and thus remains small most of the time. This has also been confirmed by our simulation results. For example, for $\theta = 1$ and $\theta_1 = 1$, in environment N_1 the mean bit duration (normalized to the bit duration of the fixed rate system) is 0.72 for S_2 and 0.09 for S_3.
- When the size of the groups that are located far away from the antenna increases (e.g., the case of (a) N_1 and N_2 for $\theta_1 = 0$ compared to N_1 and N_2 for $\theta_1 = 1$, (b) N_3 and N_4 for θ_1=1 compared to N_1 and N_2 for $\theta_1 = 0$, respectively), the performance of S_3 starts to degrade. This is due to the fact that larger distances from the antenna for the main groups give rise to a higher mean bit duration. For example, for $\theta = 1$, $\theta_1 = 0$ in environment N_1 the mean bit duration (normalized to the bit duration of the fixed rate system) is 0.22 whereas for $\theta = 1$, $\theta_1 = 1$ in environment N_3 it is equal to 0.39. However, the performance of S_3 remains significantly superior to that of S_2 due to the fact that in S_2 the mean bit duration for items demanded by groups close to the antenna is still protected from acknowledging clients that are located further away. This of course does not hold for S_2.
- The performance degradation described above is not observed for S_2 for $\theta_1 = 1$ in N_3 and N_4 compared to N_1 and N_2, respectively. This is because the slight performance decrease (due to the higher mean bit duration caused by the larger groups of clients located further away) is counter measured by the fact that

overall demand skewness (overall θ) increases. This is because for $\theta_1 = 1$, in N_3 and N_4 the sizes of these groups become a lot larger than the sizes of those of groups located closer to the antenna. Thus, an increasing majority of clients are interested in certain database subsets which is translated in overall increase in demand skewness and consequently a certain amount of performance gain.

4. Conclusion

This paper proposed a mechanism that exploits locality of demand in order to increase the performance of wireless data dissemination systems. It trades the E_b redundancy at a distance smaller than the coverage radius, for an increased bit rate for transmission of items demanded by client groups at this distance. Moreover, it protects performance from degradation caused by individual clients that demand the same information items with those demanded by client groups located elsewhere. Simulation results have been presented that reveal significant performance improvement for clients located around the area of interest.

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