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A Data Allocation Method over Multiple Wireless Broadcast Channels*

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In this paper, we concentrate on data allocation methods for multiple wireless broadcast channels to reduce the average data access time. Existing works first sorted data by their access probabilities and allocate the partitions of the sorted data to the multiple wireless channels. They employ the *Flat* broadcast schedule for each channel to cyclically broadcast all the data items allocated to it. The different access probabilities of the data items within a channel are ignored. To cope with this problem, S2AP method was proposed. It allocates a popular data item more than once per cycle to the channel to which it is assigned. The number of times that each data item is allocated reflects its access probability. However, the performance improvement of S2AP method is somewhat limited because the skewness of data access probability distribution within each channel is not large. We propose ZGMD method which first allocates data over multiple wireless channels by trying to maximize the average skewness of data access probability distributions over multiple channels. ZGMD method then computes the broadcast repetition frequencies of all the data items in each channel by using the method proposed in S2AP scheme. Finally, ZGMD method generates the broadcast disk program for multiple wireless broadcast channels. Our performance analysis shows that ZGMD method gives the better average access time than the existing methods.

Keywords: broadcast channels, data allocation, mobile clients, mobile databases, broadcast schedules

1. INTRODUCTION

The use of laptops, portable computers, and PDAs over mobile communication networks is increasing, and mobile applications such as monitoring stock market prices, traffic reports, and weather forecasts are widely available in wireless environments. In such an environment, a large number of mobile clients may be querying databases over unreliable, slow, and expensive wireless communication links. Data broadcasting is an efficient method of data dissemination that can overcome the limitations of a wireless environment, such as its low communication bandwidth and the energy constraints of mobile devices. A data server can broadcast data periodically, and mobile clients can listen on one or more channels to access the data that they require.

In a broadcast environment, mobile clients need to wait for the data that they want to appear on a channel. The time spent waiting for a data item is called its expected delay. Clearly, as the number of data items to be broadcast increases, the average expected de-

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lay increases. In a multichannel environment, data that is requested more frequently can be sent over a fast channel, which carries less data and has a short broadcast cycle length. Less popular data items can be allocated to a slow channel with a longer broadcast cycle length. Organizing data to make use of multiple broadcast channels raises a number of interesting challenges. One is the algorithm that partitions data among the channels. The server needs to generate a broadcast schedule for multiple channels in a way that reduces the average expected delay of the data items. The design of such a scheduling algorithm has already attracted significant research [1-11].

However, these works have been focused on the assignment of a data item to a channel and does not respect the different access probabilities of data items in each channel. To cope with this problem, S2AP method is proposed [12]. It allocates a popular data item more than once per cycle to the channel to which it is assigned. The number of times that each data item is allocated reflects its access probability. However, the performance improvement of S2AP method is somewhat limited. This is because S2AP method still uses the same data partition scheme as the existing works do. That is, all the existing works including S2AP method first sort data items by their access probabilities and allocate the partitions of the sorted data to the multiple wireless broadcast channels. In other words, each partition of sorted data is horizontally allocated to a single channel. As a result, the skewness of data access probability distribution in each channel becomes small. This small skewness of data access probability distribution makes S2AP method generate the less effective broadcast disk program for multiple wireless broadcast channels, which in turn increases the average data access time of mobile clients.

In this paper, we propose ZGMD (Zipfian Generated Multichannel Data allocation) method which allocates data over multiple wireless channels by trying to maximize the average skewness of data access probability distributions for multiple wireless channels. In ZGMD method, we first sort data items by their access probabilities and allocate the sorted data vertically across the multiple wireless channels such that the average skewness of data access probability distributions over multiple channels is maximized. We then computes the broadcast repetition frequencies of all data in each channel by using the same method used in S2AP and generates the broadcast disk program for multiple wireless broadcast channels.

The rest of this paper is organized as follows. In section 2, we overview related work and the preliminaries required to characterize the allocation problem. In section 3, we propose ZGMD method which allocates data items to multiple wireless channels by maximizing the skewness of data access probability distributions of all channels. An example showing broadcast schedules produced by ZGMD method is also presented in section 3. Our scheme has been evaluated through experimental simulations, which are reported in section 4. Finally, section 5 provides the concluding remarks.

2. RELATED WORKS

Past works on finding optimal allocation numbers for broadcast data are based mostly on single-channel environments [13-15]. However, the optimal allocation numbers on a single channel may not remain optimal when the number of channels is increased and data items are split over multiple channels. Several algorithms have been proposed for the data allocation problem over multiple channels. In this section, we will compare five these schemes: *Flat* [1], *Bin − Packing* [2], *VF* [3], *Greedy* [4, 16], and S2AP [12]. Table 1 shows the main characteristics of these algorithms.

Table 1. Related works.

Data Allocation Schemes	Basic Allocation Concept	Complexity	Characteristics
Flat [1]	$\frac{N}{K}$	$O(K)$	Simple, low computational overhead, long data access time for skewed access pattern
Bin-Packing [2]	Based on bin-packing, Allocates a data item to the next channel (bin) if the current bin temperature exceeds the ave. bin temperature	$O(N\log N)$	Simple, data temperature is considered, needs to run cooling process periodically
VF^K [3]	Heuristic method to compose the allocation tree which minimize the level costs	$O(KN^2\log K)$	Average expected delay is close to the optimal schedule, high computational complexity and space to maintain cost table
Greedy [4]	Greedy algorithm to determine split-points which minimize the average expected delay	$O((N+K)\log K)$	Average expected delay is close to the optimal schedule, relatively low computational overhead
S2AP [12]	Greedy algorithm to determine split points &repetition frequencies of data which minimizes the ave. expected delay	$O(KN^2)$	Higher computational complexity than Greedy method [4] but its performance is better

These algorithms all use the following system model: There are K broadcasting channels, each of which is denoted by C_i, where $1 \le i \le K$. A server broadcasts N data items to mobile clients over the K channels. Each data item d_j is of the same size and it has its own access probability p_j where $1 \le j \le N$ and $\sum_{j=1}^{N} p_j = 1$. We assume that the access probability p_j of data item d_j is always greater or equal to the access probability p_i of data item d_i for $1 \le i \le j \le N$. In other words, data items $d_1, d_2, \ldots, d_N$ are in the descending order of their access probability $p_1, p_2, \ldots, p_N$. Each channel C_i broadcasts N_i data items, and the total number of data items is $\sum_{i=1}^{K} N_i = N$. Each channel broadcasts its data items cyclically. Time is slotted into units called ticks, which are defined as the amount of time necessary to transmit a unit of data. A mobile client requests a single item at a time. Requests occur independently at a constant average rate, and p_j does not vary from tick to tick. It is also assumed that clients know a priori the contents of the channels. This simplifying assumption is made because the indexing problem is orthogonal to the channel allocation problem: We may assume that there is an index channel which supplies data channel information to clients. For the rest of this paper, we will also use this system model to explain our proposed ZGMD method.

The performance of the data allocation schemes itemized in Table 1 was measured in terms of average expected delay (*i.e.*, average access time). Note that access time and expected delay has the same meaning and they are used interchangeably. The expected delay, denoted by w_i, is the expected number of ticks (number of data items to be skipped) that a client must wait for the broadcast of data item d_i. When N items are cyclically broadcast on a single channel, w_i become $N/2$. The single-channel average expected delay (SCAED) is the average number of ticks that a client must wait for a request and is computed as the sum of all expected delays, weighted by their access probabilities. Thus, SCAED is defined as follows:

$$\text{SCAED} = \sum_{i=1}^{K} w_i p_i = \frac{N}{2}\sum_{i=1}^{K} p_i. \tag{1}$$

When N_i items are broadcast cyclically on channel C_i, the average expected delay in receiving a data item d_j on C_i is $N_i/2$. Hence, multichannel average expected delay (MCAED) is defined as follows:

$$\text{MCAED} = \frac{1}{2}\sum_{i=1}^{k}(N_i \sum_{d_j \in C_i} p_j). \tag{2}$$

This equation was used to measure the performance of the allocation schemes for multiple wireless broadcast channels.

The *Flat* scheme simply allocates an equal number of data items to each channel. It can work quite efficiently if all the data items have approximately equal access probabilities. However, this does not reflect the usual situation in practice, and a server needs to respect the difference in the access probabilities of data items. This is why skewed allocation methods such as *Bin-Packing*, *VF*^{k}, and *Greedy* were proposed. *Bin-Packing* creates a broadcast schedule, which nearly equalizes the total access probability of each channel. *VF*^{k} uses a heuristics to construct an allocation tree with variant fan-out. The *Greedy* method also uses a heuristic algorithm to determine split-points for different channels (partitions).

As we mentioned earlier, these schemes aim to schedule broadcasts by finding points at which to split data between channels so as to minimize the average expected delay. However, all the data items allocated to the same channel will share the same expected delay, even though they all have different access probabilities. To cope with this problem, S2AP (Sensitive to Access Probability) method is proposed. It allocates some data items several times to a single channel. First, allocation numbers are determined, which are the number of times that each data item will be allocated in a major broadcast cycle. Then, each data item is assigned to one of the channels. Finally, the items are allocated to their assigned channels the number of times specified by their allocation numbers.

S2AP method proposed two new channel average expected delays called S2AP-SCAED and S2AP-MCAED. The S2AP-SCAED is derived from the SCAED. S2AP-MCAED, which is derived from the MCAED, is the multiple channel version of S2AP-SCAED. Assume that data items are sorted in descending order by access probability p_j, and that data items of uniform size are allocated to channels uniformly. A data item d_j is allocated t_j times in a major broadcast cycle. The total length of a major broadcast cycle over a single channel C_i is $N_i' = \Sigma_{d_j \in C_i} t_j$. Then, S2AP-SCAED is the average expected delay when a data item d_j is allocated t_j times over a single channel C_i and is expressed as:

$$\text{S2AP-SCAED} = \frac{N_i'}{2} \sum_{d_j \in C_i} \frac{p_j}{t_j}. \tag{3}$$

S2AP-MCAED is the average expected delay when a data item d_j is allocated t_j times over multiple channels C_i where $1 \leq j \leq N$ and $1 \leq i \leq K$. It is formally expressed as:

$$\text{S2AP-MCAED} = \frac{1}{2} \sum_{i=1}^{K} (N_i' \sum_{d_j \in C_i} \frac{p_j}{t_j}), \text{where } N_i' = \sum_{d_j \in C_i} t_j. \tag{4}$$

In S2AP method, it first sorts data items by their access probabilities, and tries to find the optimal partitions of the sorted data by using greedy algorithm to allocate them to the multiple wireless broadcast channels. The data allocation based on greedy algorithm creates hot and cold channels. Hot and cold channels consist of the data items with high and low data access probabilities respectively. This kind of data allocation usually gives the small data access probability differences between the successive data allocated within each channel. As a result, S2AP method is likely to give the small variation of t_i of the data d_j. This creates a problem for S2AP method since it generate the less effective broadcast disk program for multiple wireless broadcast channels, which in turn increases the average data access time of mobile clients. This kind of problem will become severe as the total number of multiple wireless broadcast channels increase.

To cope with the problem of S2AP method, we propose ZGMD method which allocates data over multiple wireless channels by trying to maximize the average skewness of data access probability distributions for multiple wireless channels. The increased skewness of data access probability distribution for each channel gives the large data access probability differences between the successive data allocated within each channel. As a result, S2AP method is likely to give the large variation of t_j of data d_j. For the rest of our paper, we now call the allocation time t_j of data d_j as the repetition frequency of data d_j. In the next section, we discuss our ZGMD method.

3. ZGMD METHOD

In this section, we propose ZGMD (Zipfian Generated Multichannel Data allocation) method that generates a broadcast program for multiple broadcast channels. ZGMD consists of three steps. In the first step, ZGMD allocates data to multiple channels so that the average skewness of data access probability distributions of all channels is maximized. Next, for the data allocated in each channel, ZGMD computes their broadcast frequencies. At the last step, by using the broadcast frequencies of data, ZGMD method generates a broadcast disk program for each channel. We first describe how to measure the average skewness of data access probability distribution for a single channel and then for the multiple channels.

3.1 Measurement of Skewness of Data Access Probability Distribution

We define a set of data access probabilities p_i of data d_i allocated in a channel C_j as the data access probability distribution for the channel C_j. To measure the skewness of data access probability distribution for a single channel C_j, we use zipfian factor θ_j in the Zipfs law expressed by the Eq. (5). In the Eq. (5), $f_{j,i}$ represents the access frequency of data d_i allocated to a channel C_j. r_j represents the descending order rank of the access probability p_i of data d_i among the data items allocated to the channel C_j. Note that G_j is a given constant in Zipfs law for the channel C_j.

$$f_{j,i} = \frac{G_j}{(r_{j,i})^{\theta_j}} \tag{5}$$

Let F_{N_j} be the sum of all the access frequencies of data items allocated to the channel C_j. We can formally define $F_{N_j} = \sum_{i=1}^{N_j} f_{j,i}$. The access probability p_i of a data item d_i allocated to the channel C_j can be defined as $p_{j,i} = f_{j,i}/F_{N_j}$. We replace $f_{j,i}$ in the above Eq. (5) by $p_{j,i} = f_{j,i}/F_{N_j}$. Then, we can represent the access probability $p_{j,i}$ of a data item d_i allocated to the channel C_j as follows:

$$p_{j,i} = \frac{G_j}{(r_{j,i})^{\theta_j} \times F_{N_j}}. \tag{6}$$

As the zipfian factor θ_j increases, the skewness of data access probability distribution for a single channel C_j also increases. Given the data access probabilities $p_{j,i}$, by using the Eq. (6), we want to compute the estimation of θ_j which represents the skewness of data access probability distribution for a single channel C_j. Let $\theta_{j,i}$ represent the θ_j which satisfies the Eq. (6) for data item d_i. Then, we can represent the Eq. (6) as follows:

$$p_{j,i} = \frac{G_j}{(r_{j,i})^{\theta_{j,i}} \times F_{N_j}}. \tag{7}$$

Assume that data item d_w is initially allocated to channel C_j such that $r_{j,w} = 1$. From the Eq. (7), we have $p_{j,w} = G_j/(r_{j,w})^{\theta_{j,w}} \times F_{N_j}$. Since $r_{j,w} = 1$, $p_{j,w} = G_j/(1^{\theta_{j,w}} \times F_{N_j}) = G_j/F_{N_j}$. From the Eq. (7), we obtain $\theta_{j,i} = \log(G_j/(p_{j,i} \times F_{N_j}))/\log(r_{j,i})$. By using $G_j = p_{j,w} \times F_{N_j}$, we can further simplify $\theta_{j,i} = \log(G_j/(p_{j,i} \times F_{N_j}))/\log(r_{j,i}) = \log(p_{j,w}/p_{j,i}))/\log(r_{j,i})$ for data item d_i where $i > w$ and $d_i \in C_j$. Then, $\overline{\theta_j}$, the estimation of θ_j for a channel C_j, is computed by averaging $\theta_{j,i}$ of all the data items d_i allocated in C_j. It is expressed as follows:

$$\overline{\theta_j} = \frac{\sum_{i \neq w \wedge d_i \in C_j} \theta_{j,i}}{N_j - 1}. \tag{8}$$

We name $\overline{\theta_j}$ as SCAZD (Single Channel Average Zipf distribution Degree) for a channel C_j. Based on SCAZD, we define MCAZD (Multi-Channel Average Zipf Distribution Degree) for K multiple channels in the following Eq. (9).

$$\text{MCAZD} = \sum_{j=1}^{K} \frac{\overline{\theta_j}}{K} \tag{9}$$

Our goal is to allocate data items $d_1, d_2, \ldots, d_N$ to K channels to maximize MCAZD.

3.2 MCAZD Allocation Method

In this section, we propose a greedy algorithm in Algorithm 1 for allocating data to K channels that increases MCAZD. Algorithm 1 first performs the initial allocation of K hottest data items $d_1, d_2, \ldots, d_K$ to the channels $C_1, C_2, \ldots, C_K$ respectively. This initial data allocation is necessary because the computation of $\overline{\theta_j}$ is possible only when each channel C_j gets the allocation of more than one data item. Algorithm 1 then finds the channel C_i among K channels for the allocation of the next d_{k+1} which gives the maximum MCAZD value. It continues to allocate $d_{k+2}, d_{k+3}, \ldots, d_N$ to K channels in the same way as it does for d_{k+1}.

Algorithm 1: MCAZD allocation

//**INPUT:**
// $d_1, d_2, \ldots, d_N$: a set of N unit sized data item d_i sorted by the decreasing order of their access probability
//$C_1, C_2, \ldots, C_K$: K number of broadcast channels
//p_i: the access probability of data d_i
//**OUTPUT:**
// Allocation of data items $d_1, d_2, \ldots, d_N$ to $C_1, C_2, \ldots, C_K$ channels
for $i = 1$ to K **do**
    Allocate data item d_i to the channel C_i;
end for

for $i = K + 1$ to N **do**
  max = 1;
  for $j = 1$ to K **do**
    //Let MD(d_i, C_j) be MCAZD when d_i is allocated to channel C_j;
    Compute MD(d_i, C_j);
    if($j > 1 \wedge$ (MD(d_i, C_j) > MD(d_i, C_{j-1})))**then**
      max = j;
    endif
  endfor
  Allocate the data item d_i to the channel C_{max};
end for

To demonstrate Algorithm 1, we use the eighteen data items shown in Table 2 where each data is associated with its access probabilities. In Table 2, we denote the data items $E, P, A, D, N, \ldots, R, Q$ as $d_1, d_2, \ldots, d_{17}, d_{18}$.

Table 2. Data items sorted by their access probabilities.

E	P	A	D	N	O	B	C	H	M	F	G	L	K	I	J	R	Q
0.25	0.18	0.14	0.1	0.09	0.06	0.06	0.06	0.05	0.04	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01

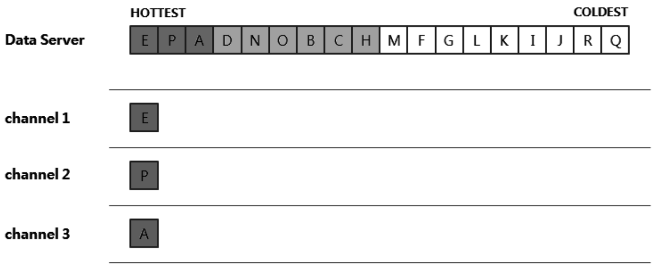
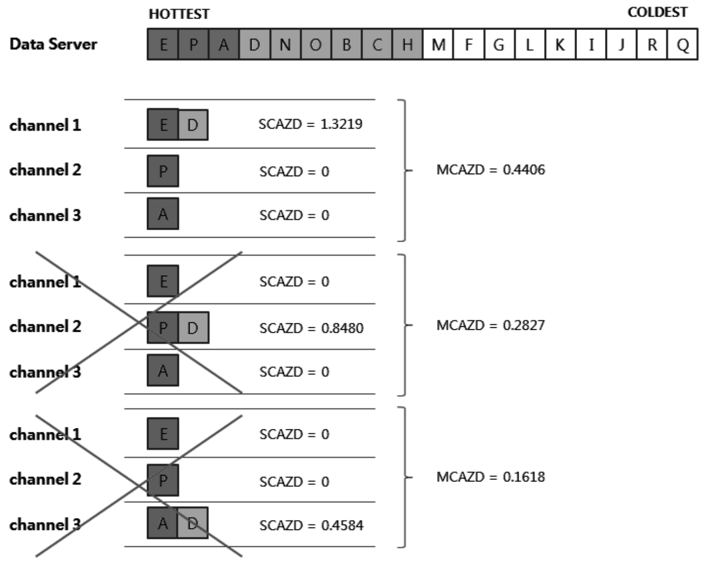


Fig. 1. Initial data allocation in MCAZD allocation algorithm.

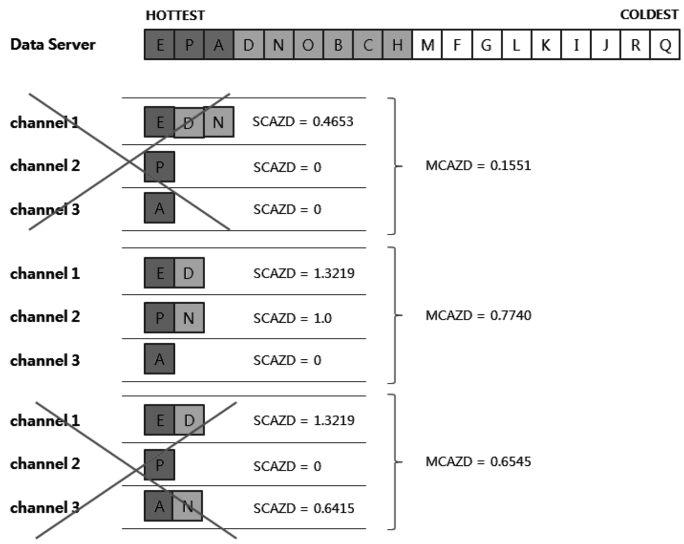
As shown in Fig. 1, Algorithm 1 initially allocates the first three hottest data items *E*, *P*, and *A* in Table 2 to the channels C_1, C_2, and C_3 respectively. The SCAZDs of the channels 1, 2, and 3 are set to 0. Algorithm 1 then tries to find the right channel for the allocation of the fourth hottest data *D*. For this, it first computes three SCAZDs $\bar{\theta}_1$, $\bar{\theta}_2$, and $\bar{\theta}_3$ when it allocates *D* to the channels C_1, C_2, and C_3 respectively. The SCAZD for the channel C_1 is computed as $\bar{\theta}_1 = \frac{\theta_{1,4}}{N_1 - 1} = \frac{\frac{\log \frac{p_{1,1}}{p_{1,4}}}{\log r_{1,4}}}{N_1 - 1} = \frac{\frac{\log \frac{0.25}{0.1}}{\log 2}}{2-1} = \frac{\log 2.5}{\log 2} = 1.3219.$ The SCAZD for the channel C_2 is computed as $\bar{\theta}_2 = \frac{\theta_{2,4}}{N_2 - 1} = \frac{\frac{\log \frac{p_{2,2}}{p_{2,4}}}{\log r_{2,4}}}{N_2 - 1} = \frac{\frac{\log \frac{0.18}{0.1}}{\log 2}}{2-1} = \frac{\log 1.8}{\log 2} = 0.8480.$ The SCAZD for the channel C_3 is computed as $\bar{\theta}_3 = \frac{\theta_{3,4}}{N_3 - 1} = \frac{\frac{\log \frac{p_{3,3}}{p_{3,4}}}{\log r_{3,4}}}{N_3 - 1} = \frac{\frac{\log \frac{0.14}{0.1}}{\log 2}}{2-1} = \frac{\log 1.4}{\log 2} = 0.4854.$ By using $\bar{\theta}_1$, $\bar{\theta}_2$, $\bar{\theta}_3$, Algorithm 1 computes the three MCAZDs when *D* is allocated to C_1, C_2, and C_3. When we allocate *D* to the channel C_1, MCAZD is computed as $\sum_{j=1}^{3} \bar{\theta}_j / 3$ = (1.3219 + 0 + 0)/3 = 0.4406. When *D* is allocated to the channel C_2, the MCAZD is computed as (0 + 0.8480 + 0)/3 = 0.2827. When *D* is allocated to the channel C_3, the MCAZD is computed as (0 + 0 + 0.4854)/3 = 0.1618. Fig. 2 (a) shows these three MCAZDs 0.4406, 0.2827, and 0.1618. Since 0.4406 is the maximum of the above three MCAZDs, Algorithm 1 allocates the data item *D* to the channel C_1.

In the next iteration, Algorithm 1 tries to find the right channel for the allocation of the fifth hottest data *N*. It computes three SCAZDs $\bar{\theta}_1$, $\bar{\theta}_2$, and $\bar{\theta}_3$ when it allocates *N* to the channels C_1, C_2, and C_3 respectively. The SCAZD for the channel C_1 is computed as $\bar{\theta}_1 = \theta_{1,5}/(N_1 - 1) = ((\log p_{1,1}/p_{1,5})/(N_1 - 1) = (\log(0.25/0.09)/\log 3)/(3 - 1) = \log 278/(2 \cdot \log 3) = 0.4653$. Similarly, Algorithm 1 computes $\bar{\theta}_2 = \log 2/\log 2 = 1.0$ and $\bar{\theta}_3 = \log 1.56/\log 2 = 0.6415$. Algorithm 1 computes three MCAZDs when *N* is allocated to C_1, C_2, and C_3. When we allocate *N* to the channel C_1, MCAZD is computed as (0.4653 + 0 + 1)/3 = 0.1551. When *N* is allocated to the channel C_2, the MCAZD is computed as (1.3219 + 1.0

+ 0)/3 = 0.7740. When N is allocated to the channel C_3, the MCAZD is computed as (1.3219 + 0 + 0.6415)/3 = 0.6545. Fig. 2 (b) shows these three MCAZDs 0.1551, 0.7740, and 0.6545. Since 0.7740 is the maximum of the above three MCAZDs, Algorithm 1 allocates the data item D to the channel C_2. We keep doing the above process until all the data items are allocated to one of the three channels C_1, C_2, and C_3. We show the final result of data allocation of MCAZD method in Fig. 3.



(a) Allocation of D.



(b) Allocation of N.

Fig. 2. Intermediate data allocation in MCAZD allocation algorithm.

3.3 Generation of Data Broadcast Schedule

In this section, we explain how ZGMD generates data broadcast schedule after MCAZD allocation is done. ZGMD first computes the repetition frequencies of all the data allocated in each channel by using the following Algorithm 2 proposed in S2AP method [12]. After determining the repetition frequencies of all the data items allocated in all channels, ZGMD applies Acharya's broadcast disk technique [1] to each channel for the generation of its broadcast disk program. Fig. 4 shows the example of final data broadcast schedule which ZGMD constructed by applying both Algorithm 2 [12] and Acharya's broadcast disk technique [1] to the data allocation shown in Fig. 3. In Fig. 4, Algorithm 2 computes the repetition frequencies of data items E, D, B, M, L, and J and obtains $t_E = 6$, $t_D = 3$, $t_B = 3$, $t_M = 2$, $t_L = 2$, and $t_J = 2$. We do not explain how Algorithm 2 computes the values of t_E, t_D, t_B, t_M, t_L and t_J in this paper, since the detailed demonstration of Algorithm 2 is already given in the example 1 in S2AP method [12].

Then, Acharya's broadcast disk technique is used to generate a broadcast disk program for channel 1 as follows. First, the data items with the same repetition frequency are grouped together. In this case, we have three groups {E}, {D, B}, {M, L, J}. Next, we

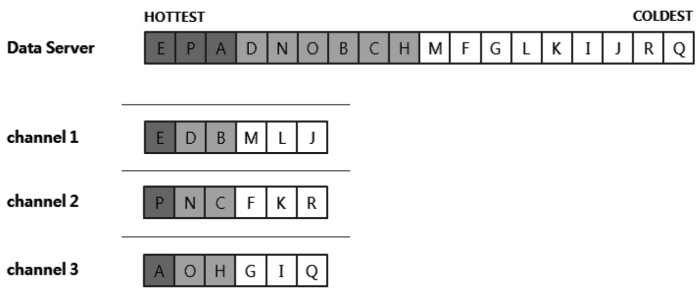


Fig. 3. Final result of data allocation in MCAZD allocation algorithm.

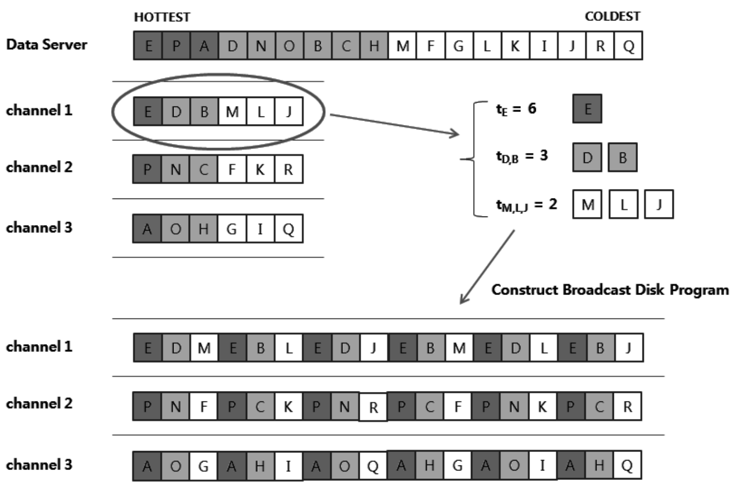


Fig. 4. Final data broadcast schedule of ZGMD method.

Algorithm 2: Repetition frequency determination in S2AP [12]

//**INPUT:**
//$u_1, u_2, \ldots, u_{Nj}$: a set of N_j data items allocated to the channel C_j by MCAZD method
//p_i: the access probability of data u_i where $p_i \geq p_{i+1}$ for i=1, $N_j - 1$
//*start* = 1, *end* = N_j, e_s = acceptable error
//**OUTPUT**
//$t_1, t_2, \ldots, t_{Nj}$: the repetition frequencies of data items $u_1, u_2, \ldots, u_{Nj}$

$k = c$ /*start value to find k*/
while $g(k, start, end) < e_s$ **do**
$$k = k - \frac{g(k, start, end)}{g'(k, start, end)}$$ /*Newton-Raphson method*/
end while
for i = *start* to *end* **do**
$$t_i = Round[\frac{p_i \times (k + p_{N_j})}{P_{N_j} \times (k + p_i)}]$$
end for

function $g(k, start, end)$
result = 0.0
for i = *start* to *end* **do**
$$result = result + \frac{p_i}{(k + p_i)}$$
end for
return (*result* – 1.0)
function $g'(k, start, end)$ /*the derivative of $g(k, start, end)$*/
result = 0.0
for i = *start* to *end* **do**
$$result = result + \frac{p_i}{(k + p_i)^2}$$
end for
return (– *result*)

compute the LCM (Least Common Multiple) of the repetition frequencies (*i.e.*, 6, 3, 2) of the three groups.

Each group is then split into smaller units called chunks. The number of chunks for each group is computed from dividing LCM by each group's repetition frequency. Finally, a chunk from each group is scheduled one by one until no chunks are left. This forms a broadcast disk program for channel 1 as shown in Fig. 4. Similarly, we can generate the remaining two broadcast disk programs for the channels 2 and 3, which are also shown in Fig. 4.

4. PERFORMANCE ANALYSIS

We analyze and compare the performance of our ZGMD method with *Flat* [1], VF^K [3], *Greedy* [4, 16], and *S2AP* [12] methods. We carried out the simulation for the performance comparison on an Intel Core Duo Processor with 3.0GHz CPU and 4GB memory. To model the nonuniform (or skewed) data access pattern of mobile clients, we use a Zipf distribution with a parameter. Note that the Zipf distribution is typically used to model nonuniform access patterns [17]. It produces access patterns that become increasingly skewed as increases. In this simulation, we set the value of θ to 0.95 to model a skewed access pattern. This access pattern is common in broadcasting environments [17]. The various parameters used in the simulation are tabulated in Table 3.

Table 3. Simulation parameters.

Simulation Parameters	Value Range	Default Value
K: the number of broadcast channels	1~10	5
θ: Zipfian parameter	0.0~1.0	0.95
N: the number of broadcast data	500~5000	1000

We choose the average access time of a mobile client as our primary performance metrics. The average access time is measured by averaging the access time of a mobile client over 10,000 simulation runs. The access time (*i.e.*, expected delay) of a mobile client represents the amount of time that the mobile client must wait for accessing the broadcast of a single data item. Note that we measure the access time in terms of broadcast units. A broadcast unit represents an amount of time taken to broadcast a single data item. In the following section, we analyze the performance of *Flat*, VF^K, *Greedy*, S2AP, ZGMD methods over various parameter values.

4.1 Effects of the Number of Broadcast Data

We varied the number of data items between 500 and 5,000 for $K = 5$ and $\theta = 0.95$. ZGMD performed best, as shown in Fig. 5. Compared to *Flat*, VF^K, and *Greedy*, as the total amount of data grows, the average access times of S2AP and ZGMD increase very slowly.

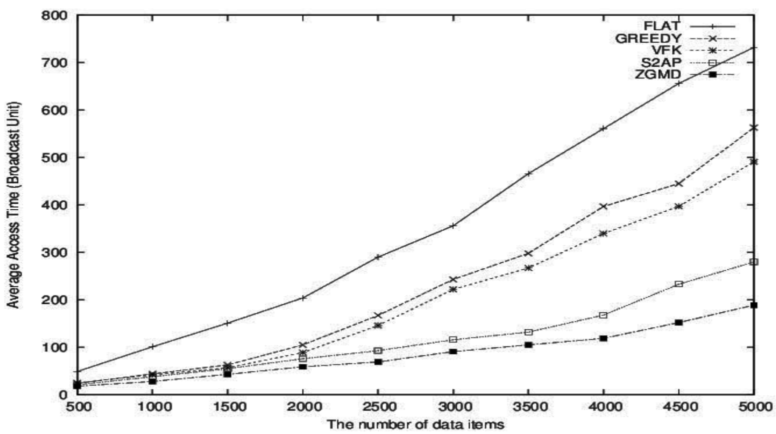


Fig. 5. Effects of the number of broadcast data.

This result shows the advantage of allocating popular data items multiple times for each channel in S2AP and ZGMD. In particular, ZGMD gives the much smaller average access time than S2AP for a large number of data items. This is because the skewness of data access probability distribution within each channel for ZGMD is much larger than that for S2AP.

4.2 Effects of the Number of Channels

Fig. 6 shows the average access time when $\theta = 0.95$ and $N = 1000$. We varied the number of channels from 1 to 10. The ZGMD outperforms *Flat*, VF^K, *Greedy*, and S2AP, especially when the number of channels is small. This is because it allocates the data items with high access probabilities many times per cycle. As the number of channels increases, the average access times of all the five methods become similar. When there are enough channels and data is widely distributed, the different data allocation schemes do not affect the performance very much.

For a single channel, ZGMD and S2AP generate the same schedule. The average access times of ZGMD and S2AP is a lot less than those of *Flat*, VF^k, and *Greedy*. This is because ZGMD and S2AP methods generate the broadcast schedule with the multiple numbers of allocations of hot data items. However, *Flat*, VF^K, and *Greedy* generate the same flat schedule for a single channel.

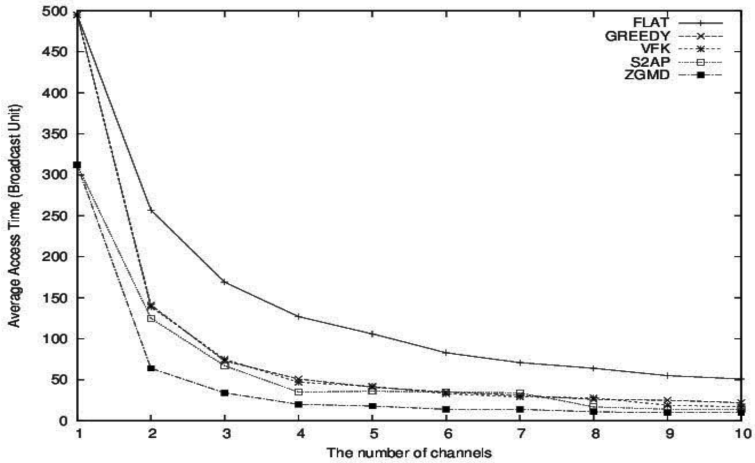


Fig. 6. Effects of the number of channels.

4.3 Effects of Varying Access Patterns

Fig. 7 shows the average data access time against the Zipfian factor. As the Zipfian factor increases, there are big differences in the data access time for the different allocation methods: *Greedy* and VF^K allocate more bandwidth to the popular items and show a lot better results than *Flat*. The average access time of *Flat* is independent of Zipfian factor as we expected. S2AP gives the smaller average access time than *Greedy* and VF^K by allocating the popular items many times per broadcast cycle in each channel. ZGMD further

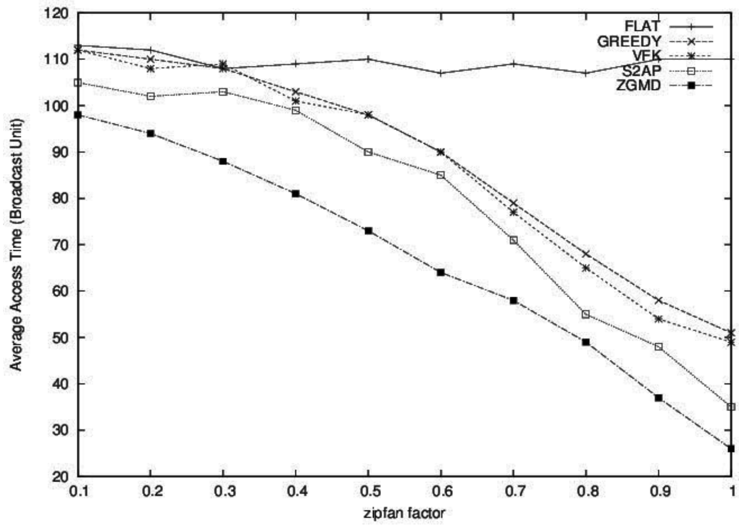


Fig. 7. Effects of varying access patterns.

achieves reductions in the average access time by maximizing the skewness of data access probability distributions of all channels.

5. CONCLUSION

We have presented a data allocation scheme for multiple wireless broadcast channels that reduces the data access time. Our scheme allocates data items over multiple wireless channels by trying to maximize the skewness of data access probability distribution for each channel. We propose SCAZD (Single Channel Average Zipf distribution Degree) and MCAZD (Multi-Channel Average Zipf Distribution Degree) to measure the skewness of data access probability distribution for a single channel and multiple channels respectively. Like S2AP method, our ZGMD method also gives a higher allocation number to a data item with a higher access probability. Simulation results show that our ZGMD gives the better average access time than all the existing methods.

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