

Dependent Data Broadcasting for Unordered Queries in a Multiple Channel Mobile Environment

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Abstract—Data broadcast is a promising technique to improve the bandwidth utilization and conserve the power consumption in a mobile computing environment. In many applications, the data items broadcast are dependent upon one another. However, most prior studies on broadcasting dependent data are restricted to a single broadcast channel environment which imposes an impractical limitation. In view of this, we explore in this paper the problem of broadcasting dependent data in multiple broadcast channels. By analyzing the model of dependent data broadcasting, we derive several theoretical properties for the average access time in a multiple channel environment. In light of the theoretical results, we develop a genetic algorithm to generate broadcast programs. Our experimental results show that the theoretical results derived are able to guide the search of the genetic algorithm very effectively, thus leading to solution broadcast programs of very high quality.

Index Terms—Data broadcast, dependent data, mobile information system, mobile computing

I. INTRODUCTION

In a broadcast-based information system [1][3][10], a server periodically broadcasts data to mobile users according to a pre-generated broadcast program by a single broadcast channel. To retrieve data items of interest, the mobile users need to wait for the appearance of the data items on the broadcast channel instead of explicitly sending data requests to the information system. Due to the above characteristics, data broadcast becomes a promising technique in a mobile computing environment since it has the following advantages:

- *Power conservation*: This is due to the fact that mobile clients need not explicitly send data requests to the information sever.
- *High scalability*: The high scalability is achieved since the system performance is independent of the number of clients.
- *High bandwidth utilization*: Data items of high interest can be received by multiple mobile clients by one transmission on the broadcast channel.

One objective of designing a broadcast-based information system is to reduce the average access time of data items. Several related research issues have attracted a considerable amount of attention, including on-demand broadcast [2] and data indexing [10]. In addition, a significant amount of research effort has been elaborated on developing the index mechanisms [13], data allocation schemes [16] and dynamic channel and data allocation schemes [7][8] in multiple broadcast channels.

Most works mentioned above were under the premise that each user requests only one data item at a time and the requests for all data items are independent. However, in many real applications, there exists dependency among data items. Consider a broadcast system to disseminate the stock information. A mobile user may submit a query like "Show me the stock information of all the LCD companies". As in this example, data items in these LCD companies are queried together and data allocation algorithms assuming independent requests are not able to effectively optimize the performance the broadcast programs. This phenomenon attracts a series of work on solving the problem of dependent data broadcast. Explicitly, the problems of dependent data broadcast can be categorized by the following two properties: (1) the number of broadcast channels (single [4] or multiple channels [9]) and (2) the constraint of the sequence of the data items (ordered [4][9] or unordered [5] queries).

Consequently, we address in this paper the problem of the broadcast program generation for unordered queries with dependent data in multiple broadcast channels. Note that the problem of broadcasting dependent data in a multiple channel environment is intrinsically difficult in that the factor of data dependency and the efficient use of multiple channels, though being dealt with separately before, are in fact entangled, thus making it more complicated to provide an effective solution to this problem. Specifically, several special cases [5][6][13] of the problem of broadcasting dependent data are shown to be NP-hard. In view of this, we shall employ the Genetic Algorithm (abbreviated as GA) in this paper to address the problem of broadcasting dependent data in a multiple channel environment. GA is a widely-used approach in the literature of soft computing and evolutionary computation. Applications of GA to solving optimization problems [11][15]. Basically, GAs are iterative procedures that search the problem solutions by an evolutionary process based on natural selection. GA maintains a population of individual candidate solutions to specific problems. An individual candidate solution can be represented as a list called a *chromosome*. In GA, a *fitness function* has to be designed to evaluate the fitness of each chromosome. The probability that each chromosome will be selected is in proportion to its fitness. The design of the fitness function is key to the effectiveness of the GA algorithms.

Explicitly, in this paper we first model the problem of broadcast program generation for unordered queries in multiple channels. By analyzing the model of dependent data broadcasting, we

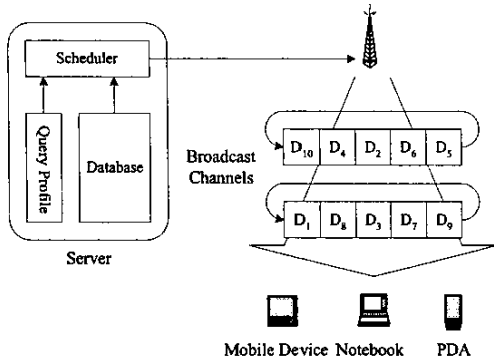


Fig. 1. The architecture of a data broadcast system

derive several theoretical properties for the average access time in a multiple channel environment. In light of the theoretical results, we then formulate the fitness functions for the GA to generate broadcast programs. Sensitivity analysis on several parameters is conducted. Our experimental results show that with the analytical results derived, the fitness functions designed are able to guide the search of GA very effectively, thus leading to solution broadcast programs of very high quality. To the best of our knowledge, there is no prior work on the broadcast program generation for unordered queries in multiple channels. This fact distinguishes this paper from others.

The rest of this paper is organized as follows. Section II gives the preliminaries of this study. Analytical models of the problem of dependent data broadcast with unordered queries are given in Section III. In light of the analysis in Section III, we devised a GA-based algorithm in Section IV. Performance evaluation on varies parameters is conducted in Section V. Finally, Section VI concludes this paper.

II. PRELIMINARIES

The system architecture is described in Section II-A. The descriptions and definitions of the problem of broadcast program generation for unordered queries are given in Section II-B.

A. System Architecture

Fig. 1 shows an example system architecture of a data broadcast system. We assume that each data item is of the same size and read-only [12]. In the beginning, since a mobile user will not know the broadcast program of the system, the mobile device should listen on a broadcast channel to wait the appearance of the broadcast program. The broadcast program contains some auxiliary information such as the data identifiers, attributes for each data item, the data index information and so on. Attributes for each data item are then used to process the query submitted by the user. The broadcast program is kept in the mobile device until it is expired. When the user submits a query to his or her mobile device, the mobile device will process this query with the aid of stored broadcast program to determine the required data items.

Query(Q_i)	$Pr(Q_i)$
$Q_1 = \{D_1, D_2, D_3\}$	40%
$Q_2 = \{D_1, D_3, D_4\}$	20%
$Q_3 = \{D_4, D_6, D_1\}$	20%
$Q_4 = \{D_1, D_2, D_5\}$	20%

Fig. 2. An example query profile

D_1	D_4	D_2
D_6	D_3	D_5

Fig. 3. An example broadcast program

The mobile device will then determine the optimal retrieve order to minimized the access time of the required data items and retrieve them from broadcast channels according to the determined retrieve order.

B. Problem Description

Suppose that the database D contains $|D|$ data items, $D_1, D_2, \dots, D_{|D|}$. For the sake of simplicity, we assume that the data items are all of equal size. From the users' point of view, a query is an indivisible request of single or multiple data item(s), and is defined as follows.

Definition 1 An *unordered* query $Q_i = \{D_{q^i(1)}, D_{q^i(2)}, \dots, D_{q^i(|Q_i|)}\}$ is a non-empty subset of all data items where $|Q_i|$ represents that number of required data items in Q_i . Note that $1 \leq q^i(j) \leq |D|$ for all $j, 1 \leq j \leq |Q_i|$.

The query profile is the aggregation of the access behavior of all users. Formally, we have the following definition.

Definition 2 A query profile Q consists of a set of $\langle Q_i, Pr(Q_i) \rangle$ pairs where $|Q|$ indicates the number of queries in Q . $Pr(Q_i)$ represents the probability that a query issued by users is Q_i . It is noted that $\sum_{i=1}^{|Q|} Pr(Q_i) = 1$.

Example 1 Consider a database D containing six data items. Fig. 2 shows an example query profile containing four queries. The query Q_3 will read data items D_4, D_6 and D_1 . Note that the read of data items need not follow this order. $Pr(Q_3) = 20\%$ shows that 20% of the queries submitted by users is the query Q_3 .

Let n represent the number of channels and L be the length of the broadcast program. A broadcast program is defined below.

Definition 3 A broadcast program P is a *placement* of all data items in D into an n by L array where $L = \left\lceil \frac{|D|}{n} \right\rceil$.

Here, we assume that $|D| = L \times n$ without loss of generality. To facilitate the further discussion, we define a function *placement* : $\{1, 2, \dots, |D|\} \rightarrow \{1, 2, \dots, L\}$ to be an onto function which maps each data item into its placement in the broadcast program.

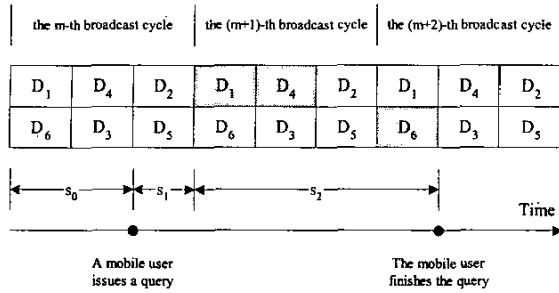


Fig. 4. An example scenario of a query

Fig. 3 shows an example of broadcast program on two broadcast channels. In this example, the value of $placement(4)$ is equal to 2 which indicates that the broadcast order of the data item D_4 in the broadcast program is 2.

Two metrics, *access time* and *tuning time*, are introduced in [10] to evaluate the performance of broadcast programs. The access time is the time elapsed from the moment a client issues a query to the moment all the relevant data are read. The tuning time is the amount of time spent by the client listening on the broadcast channels, which is a measurement of the power consumption. In this paper, we take the access time as the measurement of the performance of broadcast programs. With the above definitions, the problem of broadcast program generation for unordered queries in multiple channels is formulated as follows.

Definition 4 Given the number of broadcast channels, the database D and a query profile Q , the problem of broadcast program generation for unordered queries in multiple channels is to determine a broadcast program P which minimizes the average access time of the query profile Q .

Denote the average access time of a query Q_i as $T_{Access}(Q_i)$ and the average access time of a query file Q as $T_{Access}(Q)$. Note that the average access time of the query profile Q can be formulated as the following equation.

$$T_{Access}(Q) = \sum_{i=1}^{|Q|} [T_{Access}(Q_i) \times Pr(Q_i)] \quad (1)$$

III. ANALYTICAL MODELS

The access time of an arbitrary query Q_i can be decomposed into two portions: *startup time* and *retrieval time*. When a mobile user submits a query Q_i , the mobile device should wait until the system starts to broadcast any required data item of Q_i . This time interval is called startup time. Retrieval time is defined as the time intervals between the moment that the mobile device starts to read data items from broadcast channels and that the mobile device finishes Q_i .

Denote the size of each data item as s and the bandwidth of each broadcast channel as B . We have the following example.

Example 2 Consider the scenario shown in Fig. 4. This example assumes that the mobile user submits Q_3 shown in Fig. 2. After the user submits Q_3 , the mobile device will manipulate the stored broadcast program and obtains the optimal request order to be $D_1 \rightarrow D_4 \rightarrow D_6$. It is noted that $D_6 \rightarrow D_4 \rightarrow D_1$ is also an optimal request order. And the choice of the mobile device will not affect the access time of Q_i . In this example, the startup time of Q_3 is $s_1 = 1 \times \frac{s}{B}$ and the retrieval time is $s_2 = 4 \times \frac{s}{B}$.

Without loss of generality, we assume that the user submits a query in the m -th broadcast cycle. We also assume that the offset between the start point of m -th broadcast cycle and the moment of the mobile user submits a query (i.e., s_0) follows a uniform distribution over $(0, L)$.

To facilitate the calculation of $T_{Access}(Q)$ on a broadcast program, Q_i is refined in advance. In the beginning, all required data items of Q_i are hashed into an array H according to their placements. Let $H[j]$ represent the contents of the j -th bucket of H , and $|H[j]|$ be the number of the data items in $H[j]$. Define $cycleNo$ to be the value of "the maximum among all $|H[j]|$ " - 1. In addition, let Q'_i be the refined query of Q_i on the broadcast program. Q'_i and $cycleNo$ can be obtained by the following function.

Function QueryRefinement(Q_i, P)

Input: A query Q_i and a broadcast program P .

Output: The refined query Q'_i and the number of necessarily complete cycles $cycleNo$.

- 1: Hash all required data items of Q_i into H according to their placements.
- 2: $max \leftarrow \max_{1 \leq j \leq L} \{|H[j]|\}$;
- 3: $cycleNo = max - 1$;
- 4: $Q'_i \leftarrow \phi$;
- 5: **for** ($j = 1$ to L) **do**
- 6: **if** ($|H[j]| = max$) **then**
- 7: Randomly select *one* data item from $H[j]$, and insert the selected data item into Q'_i ;
- 8: **end if**
- 9: **end for**
- 10: return ($Q'_i, cycleNo$);

Note that $T_{Access}(Q'_i)$ is independent of the selection of data items from $H[j]$ in line 7 of the procedure QueryRefinement.

Example 3 Consider the broadcast program in Fig. 3. Suppose that $Q_i = \{D_4, D_6, D_1\}$. We first hash the placements of D_4 , D_6 and D_1 into H . $H[1] = \{D_1, D_6\}$ and $|H[1]| = 2$ since $placement(1) = placement(6) = 1$. Similarly, $|H[2]| = 1$ and $|H[3]| = 0$. The value of max is 2 since $|H[1]| = \max\{|H[1]|, |H[2]|, |H[3]|\}$, and therefore $cycleNo = max - 1 = 1$. By the loop in line 5-9, we have $Q'_i = \{D_1\}$ or $Q'_i = \{D_6\}$.

By the definitions and procedure QueryRefinement mentioned above, we have the following lemmas. For the interest of space, proofs of lemmas are omitted.

Lemma 1 Given a query Q_i and a broadcast program, denote the result of the refinement of Q_i as Q'_i and $cycleNo$. $T_{Access}(Q_i)$

can be formulated as $T_{Access}(Q_i) = T_{Access}(Q'_i) + cycleNo \times L \times \frac{s}{B}$.

Lemma 2 Consider a broadcast program, a query Q_i , and the refined query Q'_i of Q_i . Let D_x and D_y represent two randomly selected data items from Q'_i , we have $placement(x) \neq placement(y)$.

Denote the average startup time and the average retrieval time of a query Q_i as $T_{Startup}(Q_i)$ and $T_{Retr.}(Q_i)$, respectively. We then have the following equation.

$$T_{Access}(Q'_i) = T_{Startup}(Q'_i) + T_{Retr.}(Q'_i) \quad (2)$$

Let a series $a(j)$, $1 \leq j \leq |Q'_i|$, represent the sorted placements of all required data items of Q'_i , and b be $|Q'_i|$. According to the result of Lemma 2, we have the following lemmas:

Lemma 3 $T_{Startup}(Q'_i)$ can be formulated as $T_{Startup}(Q'_i) =$

$$\frac{s}{B \times L} \times \left\{ \sum_{j=1}^{b-1} \frac{[a(j+1) - a(j)]^2}{2} + \frac{[L - a(b) + a(1)]^2}{2} \right\}$$

Lemma 4 $T_{Retr.}(Q'_i)$ can be formulated as $T_{Retr.}(Q'_i) =$

$$\frac{s}{B \times L} \left\{ (L - a(b) + a(1)) \times (a(b) - a(1) + 1) + \sum_{j=2}^b [(a(j) - a(j-1)) \times (L - a(j) + a(j-1) + 1)] \right\}.$$

With Lemma 3 and 4, $T_{Access}(Q_i)$ for all $1 \leq i \leq |Q|$ can be obtained by (2) and Lemma 1. And finally, $T_{Access}(Q)$ can be calculated by (1).

IV. DESIGN OF GENETIC ALGORITHM

Fitness is the measurement of the quality of the chromosomes, and the GA is designed to search the chromosome with the highest fitness (i.e., maximize the fitness). Since the goal of dependent data broadcast is to minimize the average access time of the given query profile, the fitness function is defined as $Fitness(P) = \frac{1}{T_{Access}(Q)}$.

According to (1), $T_{Access}(Q)$ is the weighted summation of all $T_{Access}(Q_i)$. Consequently, $T_{Access}(Q)$ can be obtained by the following procedure with the aid of function QueryRefinement proposed in Section III.

Procedure CalAccessTime(Q, P)

Input: A query profile Q and a broadcast program P .

Output: $T_{Access}(Q)$ over the broadcast program P .

- 1: $T_{Access}(Q) \leftarrow 0$
- 2: **for** $i = 1$ to $|Q|$ **do**
- 3: $T_{Access}(Q) \leftarrow T_{Access}(Q) + CalAccessTimeOfQuery(Q_i, P) \times Pr(Q_i)$

TABLE I
SYSTEM PARAMETERS

Parameters	Values
The number of generations (n_{Gen})	200
The size of population (n_{Pop})	20
The probability of crossover (P_C)	0.5
The probability of mutation (P_M)	0.5
The size of each data item (s)	1000 bytes
The bandwidth of each broadcast channel (B)	80000 bps
The number of data items ($ D $)	150
The number of queries ($ Q $)	300
The average query length	15

- 4: **end for**
- 5: **return** $T_{Access}(Q)$

Function CalAccessTimeOfQuery(Q_i, P)

Input: A query Q_i and a broadcast program P .

Output: $T_{Access}(Q_i)$ on the broadcast program P .

- 1: ($Q'_i, cycleNo$) \leftarrow QueryRefinement(Q_i, P) /* Refine the query Q_i */
- 2: Calculate $T_{Startup}(Q'_i)$ and $T_{Retr.}(Q'_i)$ in accordance with the results of Lemma 3 and 4
- 3: $T_{Access}(Q_i) \leftarrow T_{Startup}(Q'_i) + T_{Retr.}(Q'_i)$
- 4: **return** $T_{Access}(Q_i) + cycleNo \times L \times \frac{s}{B}$ /* According to Lemma 1 */

V. PERFORMANCE EVALUATION

A. The System Model

We implement our GA-based algorithm with GALib [17]. In addition, we also implement a query profile generator based on the approach mentioned in [14]. The probability of the query Q_i issued by users is assumed to be $Pr(Q_i) = \frac{(\frac{1}{i})^\theta}{\sum_{j=1}^{|Q|} (\frac{1}{j})^\theta}$ where θ is the parameter of the Zipf distribution. Table I shows the system parameters in our experiments. The simulator and query profile generator are coded in C++.

B. Experimental Results

Fig. 5 and 6 show the average access time and execution time with the value of θ and the number of broadcast channels (n) varied. The value of n is ranging from 4 to 10, and the value of θ is ranging from 0 to 4. Note that $\theta = 0$ indicates that each query is of the same access probability (i.e., $Pr(Q_i) = Pr(Q_j)$ for all $1 \leq i, j \leq |Q|$).

Consider the results shown Fig. 5. The average access time decreases as the number of channels increases. This result agrees with the intuition that the increase of the network bandwidth usually decreases the average access time. However, the improvement on the average access time decreases as the number of channels increases. As a result, the determination of the number of broadcast channels should consider the balance between performance improvement and the number of channels used. The number of broadcast channels suggested by our experiment is around

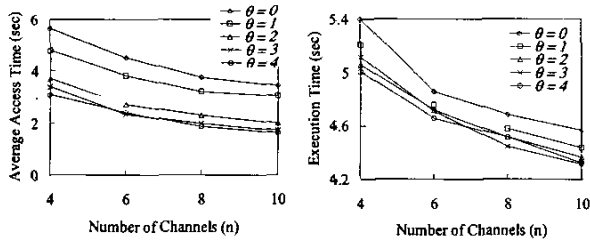


Fig. 5. The average access time with θ and n varied

Fig. 6. The execution time with θ and n varied

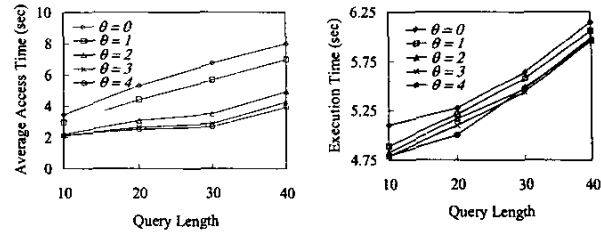


Fig. 7. The average access time with θ and query length varied

Fig. 8. The execution time with θ and query length varied

8. Fig. 5 also shows the effect of the value of θ . We can observe that the average access time decreases as the access probabilities of queries become more skewed (i.e., the value of θ becomes large). This is because that when the access probabilities of queries are skewed, only to optimize a few queries can produce high performance broadcast programs, thereby leading the quick convergence.

As shown in Fig. 6, the execution time decreases as the number of channels increases. This result is caused by query refinement. By Definition 3, a large value of n implies a short broadcast program (i.e., a small value of L). According to function QueryRefinement, the number of the required data items of each refined query Q'_i is always smaller than or equal to L . The decrease of L will cause short refined queries and therefore decreases the time to calculate $T_{Startup}(Q'_i)$ and $T_{Retr.}(Q'_i)$. We also observe that the increase of θ also slightly decreases the execution time.

Fig. 7 and 8 show the average access time and execution time with the value of θ and the query length varied. The query length is ranging from 10 to 40, and the value of θ is ranging from 0 to 4. Consider the results shown in Fig. 7. It is intuitive that the average access time increases as the query length increases. In addition, we also observe that the increase of θ will reduce the sensitivity of the average access time over the query length. The reason is that with high value of θ , only to optimize a few queries can produce high performance broadcast programs and reduce the sensitivity of the average access time over query length. Fig. 8 shows that the execution time increases as the query length increases. This is because that the calculation of $T_{Access}(Q)$ depends on the query length. In addition, we can also observe that the increase of θ also slightly decreases the execution time.

VI. CONCLUSION

We explored in this paper the problem of broadcasting dependent data in multiple broadcast channels for unordered queries. In light of the theoretical results derived, we developed a genetic algorithm to generate broadcast programs in multiple channels. Our experimental results showed that the theoretical results derived were able to guide the search of the genetic algorithm very effectively, thus leading to solution broadcast programs of very high quality.

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