Data Broadcast on a Multi-System Heterogeneous Overlayed Wireless Network

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Abstract

We propose in this paper a two-phase algorithm, named algorithm Layered-Cutting, to address the problem of broadcast program generation in a multi-system heterogeneous overlayed wireless network. The experimental results show that algorithm Layered-Cutting is able to efficiently generate broadcast programs of high quality for a multi-system heterogeneous overlayed wireless network.

Keywords: *Data broadcast, heterogeneous overlayed network, mobile computing*

1 Introduction

A multi-system heterogeneous wireless network with multiple wireless access technologies is deemed a key part of 4*G* networks [7]. A 4*G* network can be conceptually visualized as a collection of multiple independent access subnetworks. This vision leverages the relative merits of multiple cellular access systems, with significant heterogeneity in their individual characteristics such as coverage area, transmission range and channel bandwidth. By using multiple, physical or software-defined radio interfaces, mobile devices are able to switch between these wireless access technologies to obtain better service quality. Service providers should take advantage of the relative merits of different subnetworks to provide high quality network access at anytime in anywhere.

In order to provide power conserving and high scalable services in a mobile environment, a data delivery architecture in which a server continuously and repeatedly broadcasts data to a client community through a single broadcast channel was proposed in [1]. Unfortunately, most of the prior studies in data broadcast only deal with data indexing, broadcast program generation or other issues in a *single-system wireless network* (i.e, in *one* network with one or multiple broadcast channel(s)). Therefore, the approaches proposed by these studies cannot be directly used in *a multi-system heterogeneous overlayed wireless network*. We argue that with the development of 4*G* networks, designing a proper scheme to employ data broadcast on multi-system networks will become an important issue in the development of mobile information systems.

In view of this, we propose a two-phase algorithm, named algorithm Layered-Cutting, to address the problem of broadcast program generation in a multi-system heterogeneous overlayed wireless network. Specifically, algorithm Layered-Cutting consists of two phases: inter-network data allocation and intra-network data allocation, and cooperates with a designated broadcast program generation algorithm for a single-system network. For better readability, the employed broadcast program generation algorithm for a single-system network is referred to as algorithm BPG-Single (standing for Broadcast Program Generation for Single-system networks) in the rest of this paper. In inter-network data allocation phase, algorithm Layered-Cutting allocates a set of data items to each subnetwork. Since broadcast program generation algorithms are usually of high complexity, for better scalability, the times of executing algorithm BPG-Single should be minimized. To achieve this, algorithm Layered-Cutting employs an overall average access time estimation method to estimate the quality of different data allocation settings, and determines a data allocation setting with smaller *estimated* overall access time as the result of inter-network data allocation phase. After determining a proper data allocation setting in inter-network data allocation phase, algorithm Layered-Cutting steps into intra-network data allocation phase to generate one broadcast program for each subnetwork according to the number of channels in the subnetwork and the properties (including data access probabilities and object sizes) of the data items allocated to the subnetwork. To evaluate the performance of algorithm Layered-Cutting, several experiments are conducted. The experimental results show that algorithm Layered-Cutting is able to efficiently generate broadcast programs of high quality for a multi-system heterogeneous overlayed wireless network. To the best of our knowledge, there is no prior work considering data broadcast on heterogeneous overlayed networks. This characteristic distinguishes this paper from others.

The rest of this paper is organized as follows. First, problem description and formulation are given in Section 2. Then, the details of algorithm Layered-Cutting are shown in Section 3. Section 4 shows the experimental results, and finally, Section 5 concludes this paper.

2 Preliminaries

2.1 System Model

Consider a multi-system heterogeneous overlayed network $N = \{N_1, N_2, \cdots, N_{|N|}\}$ consisting of $|N|$ subnetworks, and suppose that these subnetworks are ordered by the sizes of their coverage areas in ascending order. To facilitate the following discussion, we make the following two assumptions.

1. The service area of subnetwork N_i is totally covered by that of subnetwork N_j if $j > i$.
2. When being able to connect to subnetwork N_i and subnetwork N_j simultaneously, users prefer using subnetwork N_i than using subnetwork N_j if $j > i$.

These two assumptions hold in many cases. As mentioned in [6], wireless networks with larger coverage areas are usually of higher connection fee and of lower bandwidth than those with smaller coverage areas. For example, the service area of a GPRS network is larger than the service area of a Wi-Fi network, and the service area of a Wi-Fi network is usually totally covered by a GPRS network. In addition, when being able to connect to these two networks, users usually prefer using the Wi-Fi network rather than using the GPRS network since Wi-Fi networks are cheaper and of bandwidth higher than GRPS networks.

2.2 Problem Description and Formulation

Suppose that in subnetwork N_i, the service provider allocates C_i channels to provide the data broadcast service and the bandwidth of each channel is B_i. Suppose that the database D contains $|D|$ data items, $D_1, D_2, \cdots, D_{|D|}$. Also let the size of D_i be s_i and let the access probability of data item D_i be p_i.

In this paper, we take the access time as the measurement of the performance of broadcast programs. Note that in broadcast environments, "a user issues a request" does not mean that the mobile device has to explicitly issue a data request to the server. In fact, it means that the user issues a data request to the "mobile device," and the mobile device will tune to the broadcast channel, wait for the appearance of the required data item and retrieve the required data item from the broadcast channel.

As mentioned in [5], in a *single-system network* with *one* broadcast channel of bandwidth B, to minimize the overall average access time, instances of each item have to be equally spaced, and the broadcast frequency of data item D_i should be proportional to $\sqrt{\frac{p_i}{l_i}}$, where l_i is defined as the time to broadcast D_i in the broadcast channel. That is, l_i is equal to $\frac{s_i}{B}$ where B is the bandwidth of the broadcast channel. This result is also called *square-root rule*. When square-root rule is satisfied, the lower bound of overall average access time is

$$t_{Opt.} = \frac{1}{2}\left(\sum_{j=1}^{|D|}\sqrt{p_i \times l_i}\right)^2. \qquad (1)$$

On the other hand, if the network contains multiple channels, say *ChannelNo* broadcast channels, the lower bound of overall average access time will be

$$t_{Opt.}^{Multi} = \frac{t_{Opt.}}{ChannelNo}. \qquad (2)$$

For ease of presentation, we assume that all data items have been reordered according to their $\sqrt{\frac{p_i}{l_i}}$ values in descending order in the rest of this paper.

We now consider the cases in a multi-system heterogeneous overlayed wireless network. We first observe the case that data items $D_1, D_2, \cdots, D_{|D|}$ are broadcast in a multi-system heterogeneous overlayed wireless network consisting of two subnetworks, N_1 and N_2. Since N_2 is of the largest service area, all data items have to be broadcast in N_2 in order to provide the highest data availability. On the other hand, to minimize the overall average access time, N_1 will only broadcast some data items with high broadcast frequencies (i.e., high $\sqrt{\frac{p_i}{l_i}}$ values). Therefore, we have to determine a cutting point Cut_1 so that data items from D_1 to D_{Cut_1} are broadcast in N_1 and data items from D_1 to $D_{|D|}$ (i.e., all data items) are broadcast in subnetwork N_2. Here we say that data items from D_1 to D_{Cut_1} are *allocated* to subnetwork N_1 and data items from D_1 to $D_{|D|}$ are *allocated* to subnetwork N_2. Since access time is taken as the performance metric, we should determine a proper value of Cut_1 to minimize overall average access time.

We then extend the above observation to a more general case with $|N|$ subnetworks. When we have to broadcast data items $D_1, D_2, \cdots, D_{|D|}$ in a multi-system heterogeneous wireless network consisting of $|N|$ subnetworks, N_1, N_2, $\cdots N_{|N|}$, we shall first determine the values of $|N| - 1$ cutting points, $|Cut_1|, |Cut_2|, \cdots, |Cut_{|N|-1}|$, where $Cut_i \leq Cut_j$ when $i < j$. Then, for $i = 1, 2, \cdots, |N| - 1$, data items from D_1 to D_{Cut_i} are allocated to subnetwork N_i. All data items

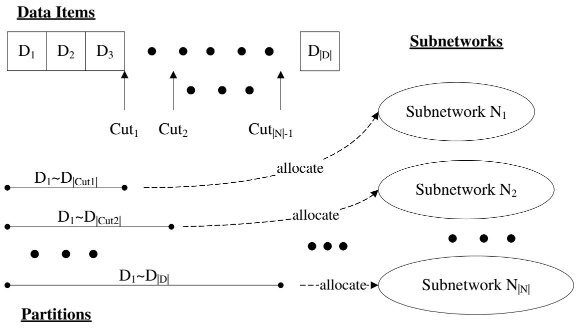

Figure 1. Flowchart of inter-network data allocation

are allocated to subnetwork $N_{|N|}$. Hence, we have the following definition.

Definition 1 A *cutting configuration* is defined as a setting of the values of $Cut_1, Cut_2, \cdots, Cut_{|N|-1}$ so that (1) $Cut_i \leq Cut_j$ if $i \leq j$ and (2) $1 \leq Cut_i \leq |D|$ for all i.

Since overall average access time is taken as the performance metric in this paper, the determination of the values of these cutting points has to be under the goal of minimizing overall average access time. This procedure is called *inter-network data allocation*. The flowchart of inter-network data allocation is shown in Figure 1.

After inter-network data allocation, each subnetwork is assigned some data items. Then, for each subnetwork, we should determine how to broadcast the assigned data items by all broadcast channels of this subnetwork. That is, to generate a broadcast program for each subnetwork. Such procedure is called *intra-network data allocation*. Fortunately, the problem of intra-network data allocation is equivalent to the problem of broadcast program generation in a single-system network with multiple broadcast channels which has been widely studied in many prior studies [3][4][8]. Hence, we will focus on inter-network data allocation in the rest of this paper and employ one prior broadcast program generation algorithm in a single-system network with multiple broadcast channels to deal with intra-network data allocation for each subnetwork.

As a consequence, the problem of broadcast program generation on heterogeneous overlayed wireless networks can be formulated as follows.

Definition 2 Given a multi-system heterogeneous wireless network $N = \{N_1, N_2, \cdots, N_{|N|}\}$, the number of allocated channels C_i in each subnetwork N_i, the number of data items, and the access probabilities and sizes of all data items, for each subnetwork N_i, we shall determine:

1. which data items will be broadcast in subnetwork N_i (i.e., a proper cutting configuration), and
2. how these data items are broadcast in subnetwork N_i (i.e., one proper broadcast program for each subnetwork).

3 Broadcast Program Generation on a Multi-System Heterogeneous Overlayed Wireless Network

3.1 Overview

In this section, we design algorithm Layered-Cutting to address the problem of broadcast program generation in a multi-system heterogeneous overlayed wireless network. Basically, algorithm Layered-Cutting is a two-phase algorithm consisting of inter-network data allocation phase and intra-network data allocation phase. The objective of inter-network data allocation phase is to determine a proper cutting configuration so that the overall average access time of the whole multi-system network is minimized. Then, in intra-network data allocation phase, algorithm Layered-Cutting will generate one broadcast program for each subnetwork according to the resultant cutting configuration. In intra-network data allocation phase, algorithm Layered-Cuting will execute algorithm BPG-Single only $|N|$ times to generate one broadcast program for each subnetwork. In addition, instead of evaluating all possible cutting configuration, algorithm Layered-Cutting only evaluates some cutting configurations with high probability to be optimal. With the above two characteristics, algorithm Layered-Cutting is able to obtain suboptimal cutting configurations efficiently.

3.2 Phase One: Inter-Network Data Allocation Phase

Since the objective of inter-network data allocation phase is only to determine a proper cutting configuration to minimize overall average access time, knowing the broadcast programs of all subnetworks is not necessary in inter-network data allocation phase. Therefore, when evaluating a cutting configuration, we use Equation (1) and Equation (2) to obtain the lower bound of overall average access time of each subnetwork and take the *weighted* summation of these lower bounds as the lower bound of the whole multi-system network. Suppose that the data access probabilities of all data items observed by subnetwork N_j are $p^j_1, p^j_2, \cdots, p^j_{|D|}$.[1] Hence, the weight of a subnetwork is defined as below.

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[1] The method to determine the values of p^j_i is omitted in this paper due to space limitation.

Definition 3 The weight of subnetwork N_j is defined as the probability that a data request is served by subnetwork N_j. Therefore, the weight of subnetwork N_j is equal to $\sum_{i=1}^{|D|} p_i^j$.

By employing Equation (1) and Equation (2), algorithm Layered-Cutting can use the lower bounds of the overall average access time of cutting configurations as the *estimated* overall average access time without executing algorithm BPG-Single.

3.2.1 Merging Subnetworks

To facilitate the design of algorithm Layered-Cutting, we first consider the effect of merging some subnetworks into a logical subnetwork. Suppose that the data access probabilities of all data items observed by the combination of subnetworks $N_1, N_2, \cdots, N_j$ are $p_1^{1\sim j}, p_2^{1\sim j}, \cdots, p_{|D|}^{1\sim j}$.[2] We then merge the combination of $N_1, N_2, \cdots, N_j$ into a *logical* single-system subnetwork, denoted as $N_{1\sim j}$, with service area of size A_j and one logical broadcast channel of bandwidth $B_{1\sim j}$. Consider a subnetwork N_i, $1 \leq i \leq j$, which has C_i broadcast channels and each is of bandwidth B_i. The weight of logical subnetwork $N_{1\sim j}$ is defined as below.

Definition 4 The weight of logical subnetwork $N_{1\sim j}$ is defined as the probability that a data request is served by one of subnetworks $N_1, N_2, \cdots, N_j$. Hence, the weight of logical subnetwork $N_{1\sim j}$ is equal to $\sum_{i=1}^{|D|} p_i^{1\sim j}$.

In addition, the aggregate bandwidth of subnetwork N_i is $C_i \times B_i$. Since the sizes of service areas of subnetwork N_i and logical subnetwork $N_{1\sim j}$ are A_i and A_j, respectively, the contribution of subnetwork N_i on bandwidth of logical subnetwork $N_{1\sim j}$ can be estimated by uniformly spreading the bandwidth from service area with size A_i to service area with size A_j. Therefore, $B_{1\sim j}$ is defined as the summation of the contributions of subnetwork $N_1, N_2, \cdots, N_j$. As a result, $B_{1\sim j}$ can be formulated as $\sum_{i=1}^{j} \frac{A_i}{A_j} \times C_i \times B_i$.

Therefore, the lower bound of the overall average access time of subnetwork $N_{1\sim j}$ can be obtained by Equation (1) with data access probabilities $p_1^{1\sim j}, p_2^{1\sim j}, \cdots, p_{|D|}^{1\sim j}$. Finally, the lower bound of overall average access time of the combination of subnetworks $N_1, N_2, \cdots, N_j$ can be approximated by the lower bound of the overall average access time of subnetwork $N_{1\sim j}$.

3.2.2 Layered Cutting

The objective of inter-network data allocation phase is to determine a proper cutting configuration (i..e, determine the values of $Cut_1, Cut_2, \cdots, Cut_{|N|-1}$) to minimize overall average access time of the whole multi-system network.

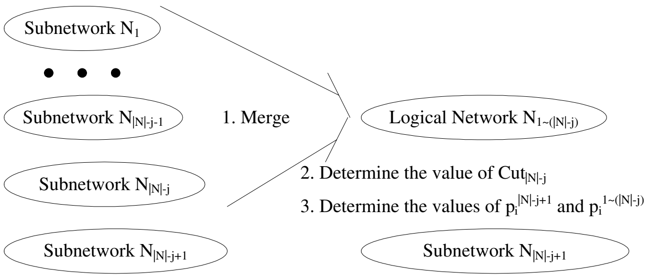

Figure 2. Layered Cutting in the *j*-th iteration

Basically, inter-network data allocation phase of algorithm Layered-Cutting is an iterative algorithm and determines the value of $Cut_{|N|-j}$ in the j-th iteration. In the first iteration, we have a multi-system network with $|N|$ subnetworks. Since subnetwork $N_{|N|}$ is of the largest service area, all data requests will be served by the combination of subnetworks $N_1, N_2, \cdots, N_{|N|}$. Hence, we have $p_i^{1\sim|N|} = p_i$ for each data item D_i. We then merge subnetworks $N_1, N_2, \cdots, N_{|N|-1}$ into logical subnetwork $N_{1\sim|N|-1}$ with service area of size $A_{|N|-1}$ and a broadcast channel of bandwidth $B_{1\sim|N|-1}$. As a result, determining the value of $Cut_{|N|-1}$ in a multi-system network with $|N|$ subnetworks is transformed into determining the value of $Cut_{|N|-1}$ in a multi-system network with *two* networks (i.e., logical subnetwork $N_{1\sim(j-1)}$ and subnetwork N_j). We then design a heuristic, named procedure Test-and-Prune, to determine the value of the cutting point between logical subnetwork $N_{1\sim(j-1)}$ and subnetwork N_j. For ease of presentation, we defer the description of procedure Test-and-Prune to Section 3.2.3 and assume that value of $Cut_{|N|-1}$ can be obtained right now. We then determine the access probabilities observed by logical subnetwork $N_{1\sim|N|-1}$ (i.e., $p_i^{1\sim|N|-1}$) and by subnetwork $N_{|N|}$ (i.e., $p_i^{|N|}$). After $p_i^{1\sim|N|-1}$ and $p_i^{|N|}$ have been calculated, algorithm Layered-Cutting finishes the first iteration and starts the second iteration.

In essence, the process of the j-th iteration is similar to that of the first iteration. In the j-th iteration, only subnetworks $N_1, N_2, \cdots, N_{|N|-j+1}$ are considered. First, subnetworks $N_1, N_2, \cdots, N_{|N|-j}$ are merged into logical subnetwork $N_{1\sim|N|-j}$. The value of $Cut_{|N|-j}$ is then determined by procedure Test-and-Prune according to $p_i^{1\sim|N|-j+1}$ which has been determined in the $(j-1)$-th iteration. Finally, the values of $p_i^{1\sim|N|-j}$ and $p_i^{|N|-j+1}$ are calculated. Inter-network data allocation phase of algorithm Layered-Cutting repeats the above steps until the value of Cut_1 has been determined. That is, after iterating $|N|-1$ times, algorithm Layered-Cutting terminates inter-network data allocation phase and steps into intra-network data allocation phase.

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[2] The method to determine the values of $p_i^{1\sim j}$ is omitted in this paper due to space limitation.

3.2.3 Determining Values of Cutting Points

After describing the process of inter-network data allocation phase in algorithm Layered-Cutting, we now describe how to determine the values of cutting points in this subsection. Note that the determination method, called procedure Test-and-Prune, is used in Section 3.2.2.

We now consider the example of the j-th iteration, and the example is shown in Figure 2. In the j-th iteration, we have to determine the value of $Cut_{|N|-j}$, where $1 \leq Cut_{|N|-j} \leq Cut_{|N|-j+1}$, so that the overall average access time of logical subnetwork $N_{1\sim(|N|-j)}$ and subnetwork $N_{|N|-j+1}$ is minimized.[3] To facilitate the following discussion, when $Cut_{|N|-j}$ is set to p, we denote the lower bound of the overall average access time of logical subnetwork $N_{1\sim(|N|-j)}$ obtained by Equation (1) as $LB_{1\sim(|N|-j)}(p)$. Also let $LB_{|N|-j+1}(p)$ be the lower bound of subnetwork $N_{|N|-j+1}$ calculated by Equation (1) or Equation (2) as $LB_{|N|-j+1}(p)$.[4] As mentioned in Section 3.2.1, the lower bound of overall average access time of the combination of subnetworks $N_1, N_2, \cdots, N_k$ can be approximated by the lower bound of the overall average access time of subnetwork $N_{1\sim k}$. Hence, the overall average access time of logical subnetwork $N_{1\sim|N|-j}$ and subnetwork $N_{1\sim|N|-j+1}$ when $Cut_{|N|-j} = p$ can be determined as $LB_{Cut_{|N|-j}}(p) = w_{1\sim|N|-j}(p) \times LB_{1\sim(|N|-j)}(p) + w_{|N|-j+1}(p) \times LB_{|N|-j+1}(p)$, where $w_{1\sim|N|-j}(p)$ and $w_{|N|-j+1}(p)$ are the weights of logical subnetwork $N_{1\sim|N|-j}$ and subnetwork $N_{|N|-j+1}$, respectively, when $Cut_{|N|-j} = p$.

To obtain the optimal value of $Cut_{|N|-j}$, it is intuitive to scan all possible values of the cutting point and to select the best one as the value of $Cut_{|N|-j}$. However, this method is unscalable since the number of data items is usually large. In view of this, we design an efficient heuristic, named procedure Test-and-Prune, to determine a proper value of a cutting point in a "test-and-prune" manner. For better scalability, the objective of procedure Test-and-Prune is to find a local optimal value, instead of the optimal value, of $Cut_{|N|-j}$. Hence, we have the following definition.

Definition 5 A value of the cutting point, say p, is said *local optimal* if $LB_{Cut_{|N|-j}}(p-1) > LB_{Cut_{|N|-j}}(p)$, and $LB_{Cut_{|N|-j}}(p+1) > LB_{Cut_{|N|-j}}(p)$.

Definition 6 A value of the cutting point, say q, is said to be *better* than another value of the cutting point, say p, if $LB_{Cut_{|N|-j}}(q) > LB_{Cut_{|N|-j}}(p)$.

The process of procedure Test-and-Prune is as follows. First, variables $left$ and $right$ are set, respectively, to the smallest and the largest possible values of $Cut_{|N|-j}$, and variable $middle$ is set to $\left\lceil \frac{right+left}{2} \right\rceil$. Procedure Test-and-Prune checks whether setting $Cut_{|N|-j}$ to $middle$ is local optimal. If so, procedure Test-and-Prune stops and suggests $middle$ as the value of $Cut_{|N|-j}$. Otherwise, procedure Test-and-Prune checks the superiorities of setting $Cut_{|N|-j}$ to $middle-1, middle$ and $middle+1$. If setting $Cut_{|N|-j}$ to $p-1$ is better than setting $Cut_{|N|-j}$ to $middle$ and $middle+1$, values from $middle$ to $Cut_{|N|-j+1}$ are pruned and $right$ is set to $middle-1$. Otherwise, when setting $Cut_{|N|-j}$ to $middle+1$ is better than setting $Cut_{|N|-j}$ to $middle-1$ and $middle$, values from 1 to p are pruned and $left$ is set to $middle+1$. The above procedure repeats until a local optimal value of $Cut_{|N|-j}$ is found.

3.3 Phase Two: Intra-Network Data Allocation Phase

The objective of intra-network data allocation phase is to determine the broadcast programs of all subnetworks according to the resultant cutting configuration. It is intuitive that generating the broadcast program of subnetwork N_j is equivalent to executing algorithm BPG-Single on subnetwork N_j with data access probabilities $p_1^j, p_2^j, \cdots, p_{|D|}^j$.

4 Performance Evaluation

4.1 Simulation Model

In addition to algorithm Layered-Cutting, we also implement algorithm Brute-Force which is able to obtain the optimal broadcast programs for multi-system networks in a brute-force manner. Similar to [2], we assume that the access probabilities of all data items follow a Zipf distribution with parameter θ. The default value of θ is set to be 0.8 with a reference to the analysis of real Web traces. We also assume that there are 1000 data items and the data sizes are assumed to follow a normal distribution with mean 1 KByte.

In the model of subnetworks, we assume that there are $|N|$ subnetworks in the multi-system heterogeneous overlayed network, and the service provider allocates three channels in each subnetwork for broadcasting data items. We also assume that subnetwork $|N|$ is able to cover the whole service area of the multi-system network and the rate between the sizes of the service areas of subnetwork i and subnetwork $i+1$ is set to 0.8. That is, $\frac{A_i}{A_{i+1}} = 0.8$ for all $1 \leq i \leq |N|-1$. In addition, the ratio between the bandwidth of one broadcast channel in subnetwork i and that in subnetwork $i+1$ is set to 2 $\left(\text{i.e., } \frac{B_i}{B_{i+1}} = 2\right)$, and $B_{|N|}$ is set to 10KBytes/sec. We use the broadcast program generation algorithm proposed in [5] as algorithm BPG-Single. That is,

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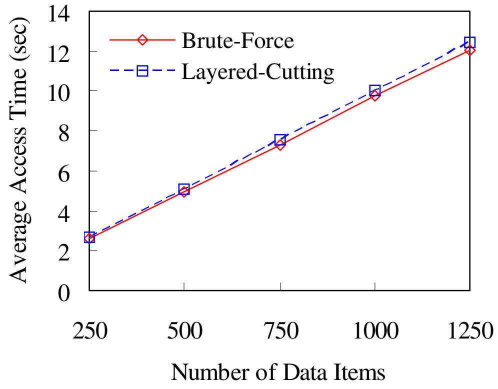
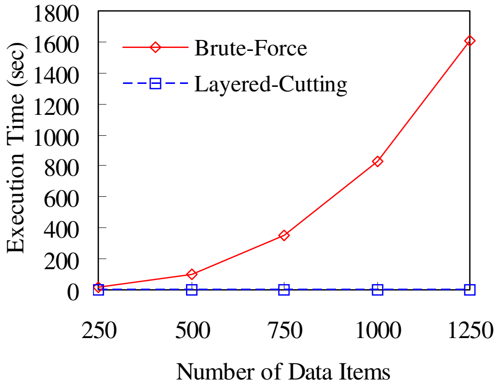
[3] The value of $Cut_{|N|}$ is defined as $|D|$.

[4] Equation (1) is designed for a single-system network with *one* broadcast channel while Equation (2) is for a single-system network with *multiple* broadcast channels.



(a) Average access time



(b) Execution time

Figure 3. Impact of the number of data items

the algorithm proposed in [5] is used to generate broadcast programs for all subnetworks in intra-network data allocation phase.

4.2 Impact of Number of Data Items

This experiment investigates the impact of the number of data items by setting the number of data items from 250 to 1250. The quality of resultant broadcast programs of algorithm Brute-Force and algorithm Layered-Cutting is shown in Figure 3a. As observed, the solutions generated by algorithm Layered-Cutting is much close to those generated by algorithm Brute-Force (i.e., optimal solutions) even the number of data items is set to 1250. In this experiment, the degradation of solutions of algorithm Layered-Cutting over solutions of algorithm Brute-Force is smaller than 4%.

Figure 3b shows the execution time of both algorithms with the number of data items varied. It is intuitive that the execution time increases as the number of data items increases. As observed in Figure 3b, execution time of algorithm Brute-Force is much sensitive on the number of data items than algorithm Layered-Cutting. The execution time of algorithm Brute-Force increases drastically as the number of data items increases. Under the same case, the execution time of algorithm Layered-Cutting only increases slightly and can be terminated within one second. This result shows that algorithm Layered-Cutting is much scalable than algorithm Brute-Force.

5 Conclusion

In this paper, we employed data broadcast in a multi-system heterogeneous overlayed wireless network and proposed a two-phase algorithm, named algorithm Layered-Cutting, to address the problem of broadcast program generation in a multi-system heterogeneous overlayed wireless networks. The experimental results showed that algorithm Layered-Cutting is able to efficiently generate broadcast programs of high quality for a multi-system heterogeneous overlayed wireless network.

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