Channel Allocation Methods for Data Dissemination in Mobile Computing Environments

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Abstract

This paper discusses several channel allocation methods for data dissemination in mobile computing systems. We suggest that the broadcast and on-demand channels have different access performance under different system parameters and that a mobile cell should use a combination of both to obtain optimal access time for a given workload and system parameters. We study the data access efficiency of three channel configurations: i) all channels are used as on-demand channels (exclusive on-demand), ii) all channels are used for broadcast (exclusive broadcast) and iii) some channels are on-demand channels and some are broadcast channels (hybrid). Simulations on obtaining the optimal channel allocation for lightly-loaded, medium-loaded, and heavy-loaded conditions were conducted and the result shows that an optimal channel allocation significantly improves the system performance.

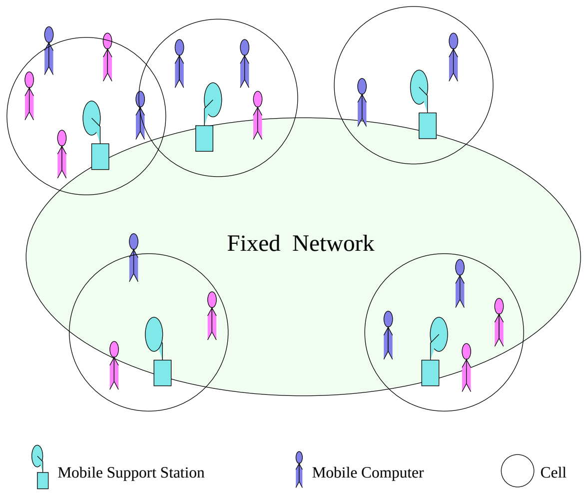

Figure 1. Wireless System Architecture.

1. Introduction

A mobile computing system consists of a set of mobile computers and stationary hosts connected by a fixed network. The mobile computers communicate with other computers through wireless communication, while the stationary hosts communicate with each other through the wired network. In order to support wireless communication for mobile computers, the geographical area covered by the system is divided into *cells*. The wireless communication in a cell is supported by a *mobile support station* (MSS), which is one of the stationary computers on the fixed network. The MSS controls the wireless communication channels in a cell and directly or indirectly provides various information services to the mobile users. As a result, it may be considered a logical data server providing and disseminating data to its mobile clients in the cell. Figure 1 shows the architecture for supporting mobile computing and illustrates the terminology such as mobile computers, MSSs, and cells.

With the widespread application of mobile communication systems, we can expect more and more people to use mobile systems as a means to access to a wide variety of information. The proposed modification on network layer protocols [7] will enable mobile computers to access information on Internet transparently, giving mobile users virtually unlimited amount of information at their fingertips. However, the limited bandwidth of the wireless channels between mobile computers and the MSSs will become the bottleneck when the service load is high. Thus, it is crucial to develop data access methods to efficiently utilize the channel bandwidth under different system loads.

Wireless broadcast has been intensively used for decades in our daily life, e.g., TV and radio program broadcast. It allows an arbitrary number of users to simultaneously receive information broadcast on the channels without any performance downgrade. We show in this paper that a mobile cell can obtain optimal data access time under different system parameters by delivering frequently accessed data items (hereafter called *hot data items*) to broadcast channels and less frequently accessed data items (hereafter called *cool data items*) on on-demand, point-to-point channels.

In this paper, we compare the data access efficiency among the channel allocation methods: i) all channels are used as on-demand channels (exclusive on-demand), ii) all channels are used for broadcast (exclusive broadcast) and iii) some channels are on-demand channels and some are broadcast channels (hybrid). The rest of the paper is organized as follows. In the next section, we will discuss the data access methods for wireless channels, broadcast scheduling strategy and the criteria for data access efficiency. In Section 3, we provide analytical and simulation models to evaluate the data access time for the on-demand and broadcast channels, respectively. In Section 4, we evaluate the performance of channel allocation methods by varying different system factors. Section 5 is a survey of previous related work and, finally, Section 6 concludes the paper.

2. Data Access Issues for Wireless Channels

In order to make efficient use of the wireless communication bandwidth and relieve the heavy communication load at the MSS, we need a better understanding of the data access methods in order to address the efficiency issues. In the following, we first describe the proposed data access methods for both of the on-demand and broadcast channels. We also discuss the issues of broadcast scheduling and describe the scheduling strategy adopted in this paper. Finally, we discuss the criteria to evaluate data access efficiency and the factors which may affect system performance.

2.1. Data Access via Wireless Channels

When a mobile computer enters a cell, it assumes no prior knowledge on how the data is provided by the MSS. Thus, it opens a connection with the MSS and simply sends a request for data item of its interest. In response, the MSS will directly deliver the data item if the data is only available through on-demand service. If the data item is also available on a broadcast channel, the MSS will reply with the *broadcast channel access information* instead. The broadcast channel access information may include the frequency of the broadcast channel, identifier of the data item, decryption key, expiration time, estimated access time and other access information. Based on the access information and preset heuristics, the mobile computer may decide whether it wants to access the data through the broadcast channel or not. If the mobile computer decides it rather receives the data through broadcast channel, it terminates the connection with the MSS and monitors the broadcast channel for the data item of its interest. Otherwise, it returns a confirmation request to the MSS, which will then will deliver the data through an on-demand channel and terminate the connection. If the mobile computer already holds the valid broadcast channel access information, it may use the information to retrieve the data from the broadcast channels without the need of contacting the MSS first.

Since broadcast channels allow simultaneous access by an arbitrary number of mobile computers, the access charge for broadcast channels is typically lower and thus encourages users to use broadcast channels. The availability of both broadcast and on-demand channel not only provides overall better channel utilization but allows users to tradeoff between access time and access costs using some heuristics preset in the mobile computers.

2.2. Broadcast Scheduling

The MSS has to schedule the broadcast of data items on the allocated broadcast channels. Broadcast scheduling is an important issue for data dissemination on broadcast channels [1,2,4]. Intuitively, data items with higher access rate should be broadcast more frequently. Therefore, algorithms in the literature use the access rates of data items as weights to randomly determine which data item will appear next in the broadcast channels.

This policy is not without a cost. Since the broadcast channels are linear media, broadcasting some of the hot data items more frequently will delay the broadcast of other data items and thus prolong the access time for less popular data items. As a result, the policy imposes unfair treatment for the users who are interested in less frequently accessed data items.

In the hybrid approach proposed in this paper, since all data broadcast on the broadcast channels are hot data items whereas cool data items are served on the on-demand channels, data disseminated on the broadcast channels are of equal importance and thus are scheduled in sequence with equal broadcast period. As a result, the access time for any broadcast data item is always bounded.

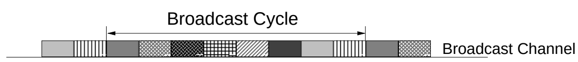

Figure 2. Broadcast Channel and Cycle.

A complete broadcast of all of the data items in a channel is called a *broadcast cycle*. Figure 2 illustrates a broadcast channel and a broadcast cycle. In a multiple broadcast channel system, the data items may be distributed to different channels in order to reduce the length of broadcast cycle. Logically, increasing the number of broadcast channels is the same as increasing the bandwidth of a broadcast channel.

Gathering the statistics on data access patterns is an important task for channel management of the MSS. Even though data access frequency is not used in our broadcast scheduling, it is the basis for selecting the data items for broadcast scheduling. Compared to the data access statistics gathering approaches discussed in the literature, the data access scenarios we depicted allow the MSS to collect the user access pattern and data access statistics through the on-demand channel communications without extra cost. When the broadcast channel access information for certain data items expires, the mobile computers are forced to communicate with the MSS again in order to obtain new broadcast channel access information. Therefore, the MSS can estimate the popularity of broadcast data items.

2.3. Data Access Efficiency

In this paper, the criteria used to evaluate data access efficiency for wireless channels is *access time*[1], which is the period from the time a mobile computer requests for a data item until the data item is received. The broadcast channels and on-demand channels introduce different access overhead for mobile computers. For the broadcast channels, the overhead is on waiting for the data item of interest to arrive. The duration between the time a mobile computer starts to monitor the broadcast channels and the time when the searched data item is located is called the *probe time*, which is the main factor influencing the access time on broadcast channels. On the other hand, the overhead for accessing data through on-demand channels is the waiting time for connecting to the MSS, which is dependent on the communication load of the system. If the load is overwhelming, the mobile computers will have to wait longer. The hybrid channel allocation method compromises the overhead of probe time and waiting time in order to reach a better system performance.

There are several factors affecting the data access efficiency of the wireless channels. For example, the sizes of data items, frequency of data requests, number and bandwidth of channels, number of users in the cell, and the size of database (i.e., number of data items) in the MSS. In this paper, we will evaluate the effects of those factors on access time of the exclusive broadcast channels, exclusive on-demand channels and hybrid channel allocation.

[1]The other criteria used for evaluating the data access performance of the wireless channels is the *tune-in time*, which represents the period of time a mobile computer spent on monitoring the broadcast channels. The tune-in time may be translated into the CPU time or battery power usage on accessing the data.

3. Modeling the Wireless Channels

In this section, we develop models for the data access performance of the exclusive on-demand and exclusive broadcast channel allocation methods. We first develop a queuing model to describe the activities on on-demand channels and run simulations based on the model to obtain the access time of the on-demand channels. Then, we develop a cost model for data dissemination on broadcast channels. Since the analysis is simple, we use the analytical model to evaluate the access time of broadcast channels during performance comparison.

Let us consider a cell in a mobile computing system. The cell consists of a MSS and m mobile computers. The MSS maintains n data items, $D_1, D_2, ..., D_n$, with average size s. The mobile computers may issue read requests[2], which have size r each, to the MSS. Let $\lambda_1, \lambda_2, ..., \lambda_n$ be the numbers of read requests generated from the m mobile computers per unit time on $D_1, D_2, ..., D_n$. We assume that the MSS supports c wireless channels and that each channel has the same bandwidth b.

3.1. On-demand Channels

We first consider the access time for a mobile computer to retrieve a data item from the MSS through the on-demand channels. The mobile computer has to establish a connection to the MSS before submitting a request. Upon receiving the request, the MSS returns the requested data items to the user. Since there are c channels in the cell, there are at most c simultaneous communication sessions. We assume that a mobile computer will not issue a new request until the previous request is completed. Therefore, there are at most m requests to be serviced in the system. To simplify our analysis, we do not consider the time for hand-shaking in order to establish the connections and the process time for MSS to retrieve the requested data items from the disk. Therefore, the service rate for an on-demand channel is:

$$\mu = \frac{b}{r+s}.$$

The aggregate arrival rate of requests from the mobile computers is:

$$\lambda = \lambda_1 + \lambda_2 + \cdots + \lambda_n.$$

The state transitions due to the arrival of data requests and completion of data requests can be modeled as the birth-death system shown in Figure 3.

Each state of the diagram denotes the number of mobile computers requesting a data item during that state. Assuming the number of potential mobile computers is greater than

[2]The mobile computers may also issue write requests too. However, we only consider read requests in this paper.

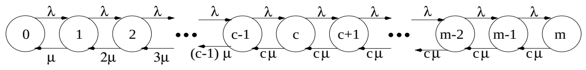

Figure 3. State transition diagram for on-demand channels.

the number of channels available in a cell, the system can be modeled as a $M/M/m/B$ queue (with c servers and m buffers).

3.2. Broadcast Channels

Next we develop the cost model for the access time of the broadcast channels, given that the mobile computer has valid broadcast channel access information about how to access the data. Since there are c channels used for broadcast, the aggregate bandwidth for broadcast channels is bc. Assume that there are x data items broadcast periodically in the broadcast channels. The size of a broadcast cycle in the aggregate broadcast channel is xs/bc. The average probe time is $xs/2bc$. Thus, the access time for retrieving data through monitoring broadcast channels is:

$$E[p] = \frac{xs}{2bc} + \frac{s}{b}.$$

4. Performance Evaluation

In this section, we compare the access time performance of exclusive on-demand, exclusive broadcast and hybrid channel allocation methods. Since there are many factors, e.g., sizes of data items and messages, frequency of data requests, number/bandwidth of the channels, number of users, and number of data items, affecting data access efficiency, we vary them to observe the characteristics of access time performance for the methods.

The access time of on-demand channels is obtained by simulation, while the access time of broadcast channels is evaluated using the cost model developed in the last section. An M/M/m/B queuing system is used to simulate the data access activities on the on-demand channels. The simulation is written in C and CSIM, which is a process-oriented simulation toolkit [10]. Each of the simulations lasts for 4,000 seconds. For clarity, we only show the performance of the hybrid method when the number of channels allocated to on-demand mode and broadcast mode ratio is 4/1. Obviously, the performance will be different when the channel assignment is different. The optimal assignment for various system parameters is presented in the next section.

In the following comparisons, we assume that a cell has 50 channels for 500 mobile users. The MSS has maintained a database of 2000 data items of 1000 bytes each. The size of a read request and the size of a returned message for broadcast channel access information are both set to 10 bytes. The average bandwidth of the channels is 1000 bytes per second. Finally, we assume that every user makes a data request every second. Therefore, the average arrival rate is 500 requests/sec. We also assume an exponential data access pattern. The distribution is controlled in such a way that 25% of the data access requests is on the top 50 most frequently accessed data items and the rest of the data access requests are on the top 500 frequently accessed data items. Thus, we assume that the exclusive broadcast method periodically broadcasts 500 data items. For the hybrid channel allocation method, the top 50 data items are available through the broadcast channels while the other data items are available through the on-demand channels. The above parameter settings are summarized in Table 1.

Parameters	Values
Number of Mobile Computers	500
Number of Data Items	2000
Number of Channels	50
Request Arrival Rate	500/sec.
Size of Data Item	1000 bytes
Size of Access Info.	10 bytes
Channel Bandwidth	1000 bytes/sec.
Simulation Time	4000 sec.

Table 1. System Parameter Settings.

4.1. Size of Data Items

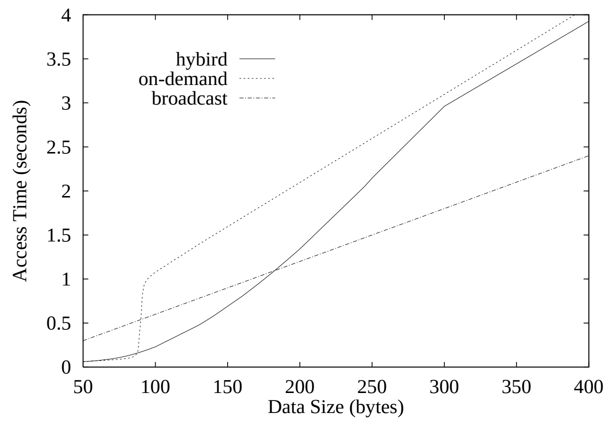

Figure 4. Access Time vs Data Size.

We increase the size of data items from 50 bytes to 400 bytes, while fixing the other parameters. As shown in Figure 4, 'on-demand', 'broadcast' and 'hybrid' represent the access time of the exclusive on-demand, exclusive broadcast, and hybrid channel allocation, respectively. The access time of the on-demand method shows that the system is rapidly overloaded after the data size is greater than 90 bytes. The leap on the access time of exclusive on-demand method is due to the increase of waiting time for mobile computers to connect to the MSS. On the other hand, the access time of the exclusive broadcast method is proportional to the size of data items. Compared to the on-demand method, the broadcast method is worse in access time when the data access load is light (data item size is less than 90 bytes) but better when the load is heavy. As shown in the figure, the hybrid method does improve overall system performance significantly when data item size is between 90 and 190. It is interesting to observe, when the load becomes very heavy (i.e., data items size is above 190 bytes), exclusive broadcast method is the best choice.

4.2. Request Arrival Rate

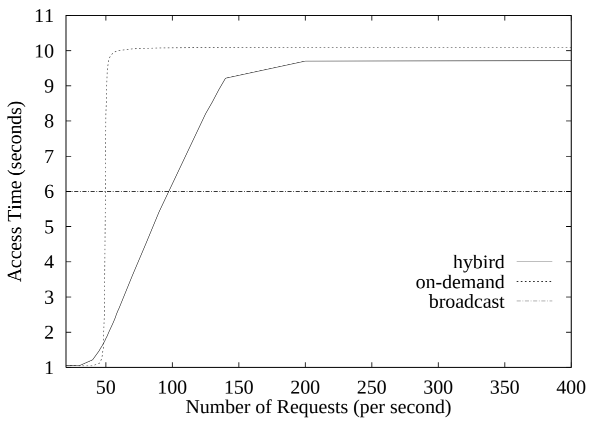

Figure 5. Access time vs Request Arrival Rate.

The request arrival rate, which may be transformed into data request frequency, is another factor affecting the system load and thus the access time of the on-demand channels. Figure 5 shows that, for exclusive on-demand, when the request arrival rate is over 50, the system is overloaded. Otherwise, the access time for on-demand method is close to the transmission time for a data item. The figure also shows that the access time of exclusive on-demand method remains constant instead of rising for an overloaded system. That is because we assume that the mobile computers do not issue new requests until their previous requests are completed.

We observe that the broadcast channels are not affected by the request arrival rate. No matter how frequent a data item is being requested, the access time for exclusive broadcast remains constant. Again the hybrid allocation gives a better access performance when request arrival rate is between 50 and 100. We varied the number of users and obtained similar results, since number of users may be transformed into data request frequency. Thus, we don't show the comparison for different number of users in the paper.

4.3. Number of Channels

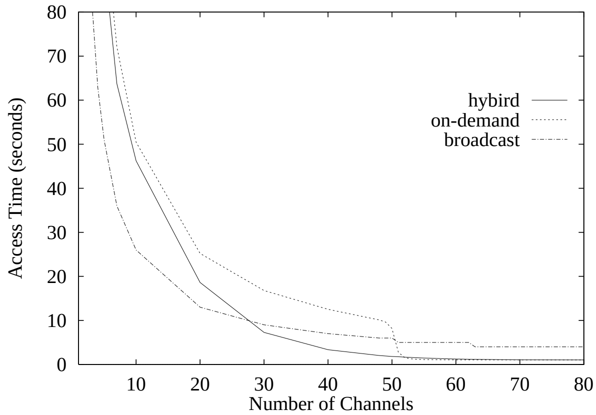

Figure 6. Access time vs Number of Channels.

We vary the number of channels in a cell to observe the change in access time. Figure 6 shows that the access time of the exclusive broadcast method drops rapidly when the number of broadcast channels increases from 5 to 20. From then on, however, increasing the number of broadcast channels has diminishing impact on the access time. This observation suggests that adding channels is not an effective way for lowering the access time for the exclusive broadcast method. For the exclusive on-demand method, the number of channels used has a dramatic impact on the access time. Under some circumstances, the system access time may improve significantly with a small increase of the number of channels. We also compared the access time of the methods by varying the bandwidth of channels and obtained similar results. In fact adding more channels has the same effect as increasing channel bandwidth while maintaining the same number of channels, and vise versa. As shown in the figure, the performance of the hybrid approach is the best when the number of channels is between 28 and 52 and is generally pretty good under all circumstances.

4.4. Number of Data Items

While the request frequency and the number of mobile computers in the system have no impact on the access time of broadcast channels, the number of data items available

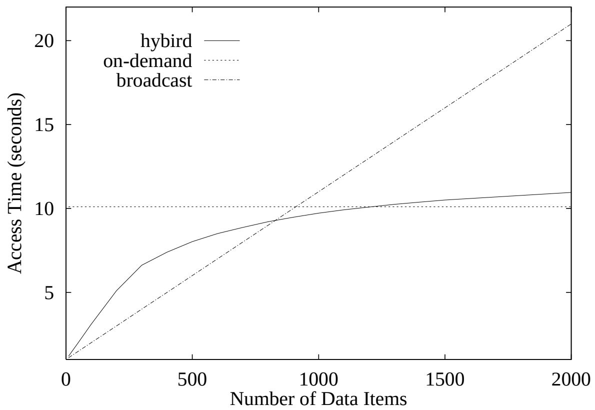

Figure 7. Access Time vs Number of Data Items.

in the MSS has no impact on the access time of on-demand channels. Therefore, on-demand channels are good for providing user access to a large database. Figure 7 shows the access time for the channel allocation methods corresponding to the number of data items available in the MSS. We observe that, with less than 900 data items, the exclusive on-demand method does better than the exclusive broadcast method. With more than 900 data items, the exclusive broadcast method has lower access time performance than that of the exclusive on-demand method, which always gives the same performance independent of the number of data items. If we offload a significant portion of the broadcast data items to on-demand channels, the overall system performance will improve. This is demonstrated by the performance of the hybrid method. When the number of data items is between 800 and 1200, hybird allocation out perform both exclusive broadcast and exclusive on demand methods.

In the previous comparisons, we have demonstrated that, when the number of data items is small, broadcast channels are in general better under various system parameters. The comparisons can be scaled to systems with much larger number of data items to be disseminated — as long as user accesses are concentrated to a small number of data items, the broadcast channels may be used to alleviate communication workload at the MSS. However, when accesses are distributed to a large number of data items, shifting on-demand channels to broadcast channels is not a good solution.

4.5. Dynamic Channel Allocation

We have shown that the hybrid channel allocation method with certain ratio of channels for broadcasting and on-demand services has better data access efficiency than the exclusive methods in general. Thus, an optimal approach for improving the data access efficiency of wireless channels is to dynamically decide the ratio of broadcast and on-demand channels based on system workload. Analysis of optimal channel assignments in a hybrid environment is quite complex and will be presented elsewhere [3]. In this paper, we use simulations to demonstrate the improvement that a dynamic channel allocation method can obtain over the exclusive on-demand method.

Workload	No. of Clients	Requests Rate
Heavy	1000	500
Medium	500	500
Light	100	45

Table 2. Workload Parameter Settings.

In our experiments, we successively change the number of data items moved from the on-demand channels onto the broadcast channels. For each number, we exhaustively test all combinations of broadcast and on-demand channels in order to find out the optimal channel allocation with the best average access time. In order to demonstrate the performance of the dynamic channel allocation method, we select different parameter values for the number of mobile computers and the request arrival rate to represent scenarios with different workloads at the MSS. The parameter settings for heavy-loaded, medium-loaded and light-loaded scenarios are listed in Table 2. The other parameters remain the same as the previous comparisons.

Figure 8, 9 and 10 show, under different system workloads, the optimal channel allocation and access time for different sizes of the hot data set. In the figures, the curves labeled as on-demand represent the data access time for exclusive on-demand allocation of the channels, while the curves labeled as optimal represents the data access time for optimal allocation of the channels.

As shown in Figure 8, a heavily loaded system may significantly improve the access time by moving some of the hot data items to the broadcast channels. The difference between the access time for on-demand and optimal channel allocation represents the improvement obtained for the corresponding hot data set size. In this experiment, broadcasting 500 data items on 33 broadcast channels results in the best average data access time: 11.35 seconds. Comparing to the access time for exclusive on-demand method, i.e., 20.14 seconds, it is a 43.64% improvement.

Similarly, Figure 9 shows that the dynamic channel allocation method out-performs the exclusive on-demand method in the medium-loaded environment. When 350 hot items are broadcast on 30 channels, the optimal access time is 9.26 seconds, which represents a 8.32% of improvement over the exclusive on-demand method.

Finally, Figure 10 shows that the exclusive on-demand

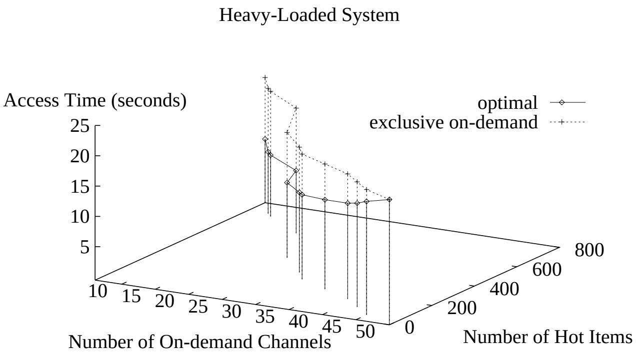

Figure 8. Optimal Access Time for a Heavy-loaded System.

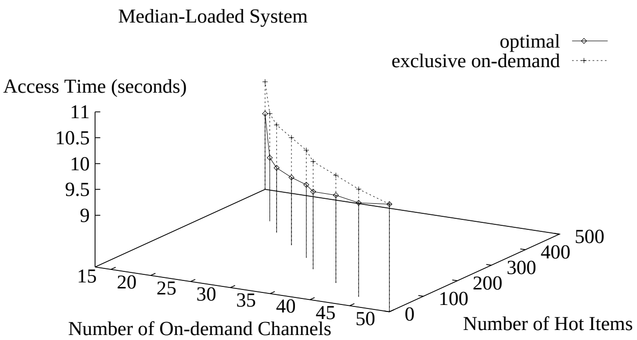

Figure 9. Optimal Access Time for a Medium-loaded System.

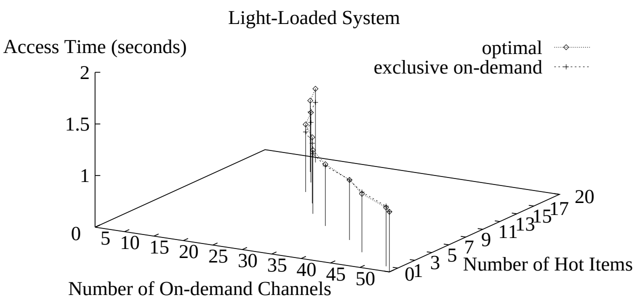

Figure 10. Optimal Access Time for a Light-loaded System.

method is almost as good as the dynamic channel allocation for the light-loaded scenario. However, the optimal channel allocation still allocates 9 channels to broadcast 3 hottest data items. This allocation results in the best average data access time of 1.066 seconds which stands for 1.48% of improvement over the 1.082 seconds of the exclusive on-demand method.

Table 3 summarizes the comparisons, under different workload scenarios, between the access time for dynamic channel allocation and that for exclusive on-demand method.

Workload	Heavy	Medium	Light
On-demand/Broadcast	17/33	20/30	41/9
Top Data Items	500	350	3
Optimal Access Time	11.35	9.26	1.066
On-demand Access Time	20.14	10.08	1.082

Table 3. Optimal Channels Allocation Simulation Result.

5. Previous Work

Several organizations for indexing and filtering broadcasted data have been proposed in the literature [5,6,9]. These papers use index, hashing, and signature techniques to provide auxiliary information, which is interleaved with the data items in the broadcast, for data accessing on the broadcast channels. The main criteria of the performance used in the papers is the tune-in time. The main issue is to see, with certain access time delay, how much tune-in time may be saved.

In order to efficiently use the network bandwidth, some of the researchers proposed to use the broadcast channels as broadcast file systems [1,2] or broadcast channels [4]. [2] focused on scheduling of the data broadcast. Two heuristics for broadcast scheduling were proposed to minimize the system access time. In addition to the scheduling problem, [1] discussed the issues for caching broadcasted data items. New cache management policies which took into consideration access and broadcast frequencies of data items were developed and presented with simulation studies. [4] provided an architecture for wireless information services and discussed the broadcast and on-demand channels. However, they chose a different scheduling strategy and assumed one logical on-demand channel and one logical broadcast channel of different bandwidths. Thus, their model and analysis is different from ours. There is no simulation results and comparisons in the paper.

All of the three papers propose to schedule the data items for broadcast based on their access frequencies. The strategy results in unbounded access time of the broadcasted data items, because some data items may be pushed back by frequently broadcasted data items. The users do not know how long they should monitor the broadcast channels to decide if the data items are available on the broadcast channels.

6. Conclusion

Wireless broadcast is an important technique for disseminating data to mobile users, because it scales up to an arbitrary number of users. In this paper, we study the data access performance of a hybrid system which combines the broadcast and on-demand services. In this system, hot data items are broadcast, whereas cool data items are served on on-demand channels. We studied and compared the performance of the hybrid method with systems where channels are used exclusively for broadcast or on-demand services. We show that by separating hot and cool items, we can broadcast all hot items on the broadcast channel sequentially without worrying about unbounded access delay on cool items caused by broadcast scheduling methods based on data access frequencies.

We developed models for evaluating the access time performance of the on-demand channels (by simulation) and broadcast channels (by analysis). Then, we conducted comparisons on access time among exclusive on-demand, exclusive broadcast and hybrid channel allocation methods by varying values of system parameters such as the size of data items, request arrival rate, number of channels in the cell, and number of data items accessible in the MSS. The results show that broadcast channels outperform on-demand channels when the data size is large, the request arrival rate is high, and when the bandwidth of the channels is low. In other words, broadcast channels perform very well when the system is overloaded. On-demand channels perform the best when the system load is light. The hybrid maintains a very good performance under all of the circumstances and sometimes out-performs both exclusive methods.

From the comparisons, we observe that broadcast channels do not scale up with the number of data items accessed, while on-demand channels do not scale up with the number of users in the cell. Both methods are sensitive to the number of channels in the cell. The efficiency of broadcast channels may be significantly improved by adding the first few more channels. However, after some point, increasing the number of channels does not improve the efficiency much. On the other hand, the access time of on-demand channels might be dramatically improved by adding a few channels to the system, since our experimental results show abrupt performance downgrade behavior for the on-demand channels. Furthermore, we conducted simulation to show that dynamic channel allocation may reach a optimal performance and thus utilize the system bandwidth more efficiently.

As for the future work, an algorithm for dynamic channel allocation is necessary to complement our simulation study and to make the channel management more effective. Since the best channel allocation strategy is to adapt dynamically with respective to various workload of the system, research on correlating dynamic channel allocation problem with the system workload is necessary.

References

[1] S. Acharya, R. Alonso, M. Franklin & S. Zdonik, "Broadcast Disks: Data Management for Asymmetric Communication Environments," Department of Computer Science, Brown University, Technical Report No. CS-94-43, December 1994.

[2] T.-C. Chiueh, "Scheduling for Broadcast-based File Systems," *NSF MOBIDATA workshop at Rutgers University, New Brunswick, NJ*, November 1994.

[3] Qinglong Hu, D.L. Lee & W.-C. Lee, "Optimal Channel Management for Mobile Computing Systems," *submitted for publication*.

[4] T. Imielinski & S. Viswanathan, "Adaptive Wireless Information Systems," *Proceedings of SIGDBS (Special Interest Group in DataBase Systems) Conference, Tokyo, Japan*, October 1994.

[5] T. Imielinski, S. Viswanathan & B. R. Badrinath, "Power Efficiency Filtering of Data on Air," *Proceedings of the International Conference on Extending Database Technology*, 1994, 245–258.

[6] T. Imielinski, S. Viswanathan & B. R. Badrinath, "Energy Efficiency Indexing on Air," *Proceedings of the International Conference on SIGMOD*, May 1994, 25–36.

[7] J. Ioannisdis, D. Duchamp & G. Q. Maguire Jr., "IP-based Protocols for Mobile Interworking," *Proceedings of the International Conference on SIGCOMM*, 1991, 235–245.

[8] R. Jain, *The Art of Computer Systems Performance Analysis*. John Wiley & Sons, Inc., 1991.

[9] W.-C. Lee & D.L. Lee, "Using Signature Techniques for Information Filtering in Wireless and Mobile Environments," *Special Issue on Databases and Mobile Computing, Journal on Distributed and Parallel Databases*, Vol. 4, No. 3, July 1996, 205–227.

[10] Mequite Software, Inc., *CSIM17 Users' Guide*.