

PhD Dissertation



**International Doctorate School in Information and
Communication Technologies**

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**A FRAMEWORK FOR DYNAMIC
HYBRID SCHEDULING STRATEGIES IN
HETEROGENEOUS ASYMMETRIC
ENVIRONMENTS**

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Abstract

The increasing growth of wireless access networks, proliferation of the Internet and gradual deployment of broadband networks has already given birth to a set of information-centric applications based on data transmission. Efficient scheduling techniques are necessary to endow these applications with advanced data processing capability. Broadly all data transmission applications are divided into (1) push and (2) pull systems. Hybrid scheduling, resulting from an efficient combination of these two types of data delivery, often exploits the advantages of both the schemes. The objective of this dissertation is to investigate and develop a novel hybrid scheduling platform by effectively combining broadcasting (push) of popular data and dissemination (pull) of less popular data. One major advantage of this algorithm is dynamic computation of cut-off-point, used to segregate the popular and less-popular data items, without any prior knowledge or assumptions. In order to achieve a better performance, the framework is enhanced to allow a set of consecutive push and pull operations, depending on the probabilities of the data items present in the system. The framework also incorporates practical issues like clients' impatience leading to clients' departure and transmission of spurious requests. A new client's priority-based service classification scheme is proposed to provide differentiated QoS in wireless data networks. The framework proceeds further to incorporate dynamic hybrid scheduling over multiple channels. Performance modeling, analysis and simulation study points out efficiency of the entire framework.

Keywords: Data broadcasting, scheduling, asymmetric-wireless environment, push-pull, hybrid systems, cut-off point, client's impatience, anomalies, client's priority and classification, repeat-attempts, performance guarantee, multiple channels, queuing systems, Markov Chain.

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Chapter 1

Introduction

The recent advancement and ever increasing growth in web technologies has resulted in the need for efficient scheduling and data transmission strategies. The emergence of wireless communication systems have also added a new dimension to this problem by providing constraints over the low-bandwidth upstream communication channels. While today's wireless networks offer voice services and web-browsing capabilities, the actual essence of future generation (3G and Beyond 3G) wireless systems lie in efficient data services. Guaranteeing precise quality of service (QoS), such as the expected access-time or delay, bandwidth and blocking are perhaps the most salient features of such data services. To extract the best performance and efficiency of a data transmission scheme, one needs a scalable and efficient data transmission technology. In such data transmission systems, there often exists asymmetry due to any of the following factors:

1. The downstream communication capacity (bandwidth from server to client) may be much higher than the upstream communication capacity (bandwidth from client to server);
2. The number of clients is significantly larger than the number of servers.
3. In information retrieval applications, the clients make requests to the server through small request messages that results in the transmission

of much larger data items. In other words, asymmetry remains in the size and amount of messages in uplink and downlink transmission.

1.1 Push-Pull and Hybrid Scheduling

Broadly, all data dissemination applications have two flavors. In a *push-based system*, the clients continuously monitor a broadcast process from the server and obtain the data items they require, *without making any requests*. Thus, the average waiting time of the clients become half of the broadcast cycle. For unit length data items, this result boils down to the half of the total number of items present in the system. The broadcast schedule can be determined online, using a flat round-robin scheme or offline using a Packet Fair Scheduling (PFS) scheme. In contrast, in a *pull-based system*, the clients initiate the data transfer by sending requests *on demand*, which the server schedules to satisfy. The server accumulates the client's requests for less-popular items in the pull queue. Subsequently, an item from the pull queue is selected depending on specific selection criteria. This selection criteria depends on the specification and objective of the system. Most request first (MRF), stretch-optimal, priority or a combination of these techniques is often used. Both push and pull scheduling schemes have their own advantages and disadvantages. While the push scheduling is not affected by the uplink channel constraints, it suffers from wasting resources in downlink wireless channels by repeatedly transmitting the less popular items. Also, for huge set of data items the average length of the push-based broadcast schedule becomes quite higher. On the other hand, the pull-based data dissemination scheme is performed on the basis of explicit clients' requests, but such client-requests are bounded by the uplink resource constraints.

Hence, neither push nor pull alone can achieve optimal performance [32].

A detailed overview of the published research works on wireless data broadcast can be found in [51]. Therefore, the search for efficient hybrid scheduling, which explores the efficiency of both push and pull strategies, continues. Example of hybrid push-pull systems include the Huges Network System DirecPC Architecture [23], that uses satellite technology to give a fast, always-on Internet connection; the Cell Broadcast Service (CBS) that enables to deliver short messages to all the users in a given cell in both GSM and UMTS systems [47]; and the Service Discovery Service in networks of pervasive devices [13]. The general notion of hybrid scheduling lies in dividing the entire set of data items into two parts: *popular items* and *less-popular items*. The scheduler pushes the popular data items at regular intervals. It also accumulates the client's requests for less-popular items in the pull queue and selects an item depending on the specific selection criteria. A wise selection of the cutoff-point, used to segregate the push and pull sets has the power to reduce the overall expected waiting time of the hybrid system. However, most of the hybrid scheduling are based on homogeneous (often unit-length) data items. The effect of heterogeneity, with items having different lengths, needs to be considered to get an efficient, hybrid scheduling strategy for asymmetric environments.

1.2 Client's Impatience

In practical systems, the clients often loose their patience, while waiting for a particular data item. This results in two-fold effects: (1) the client might get too impatient and leave the system after waiting for a certain time; This is often termed as *balking*. Excessive impatience might result in client's antipathy in joining the system again, which is better known as *reneging*. The performance of the system is significantly affected by this behavior of the clients. The scheduling and data transmission system needs

to consider such impatience resulting in balking and reneging with finite probability. (2) the client may also send multiple requests for the required data item. Multiple requests by even a single client can increase the access probability of a given item in a dynamic system. In existing scheduling schemes, the server is ignorant of this ambiguous situation and considers the item as more popular, thereby getting a false picture of the system dynamics. Hence, the effects of client's impatience leading to spurious requests and anomalous system behavior needs to be carefully considered and resolved to capture a more accurate, practical behavior of the system.

1.3 Service Classification and Differentiated QoS

Diversification of personal communication systems (PCS) and gradual penetration of wireless Internet have generated the need for *differentiated services*. The set of clients (customers) in the wireless PCS networks is generally classified into different categories based on their power and importance. Activities of the customers having higher importance have significant impact on the system and the service providers. The goal of the service providers lies in minimizing the cost associated in the maintenance of the system and reducing the loss incurred from the clients' churn rate. However, the current cellular systems and its data transmission strategies do not differentiate the QoS among the clients, i.e., the sharing and management of resources do not reflect the importance of the clients. Although most of the service providers support different classes of clients, the QoS support or the service level agreements (SLA) remains same for all the client-classes. Future generation cellular wireless networks will attempt to satisfy the clients with higher importance before the clients having comparatively lower importance. This importance can be determined by the amount of money they have agreed to pay, while choosing a particular

type of service. Deployment of such differentiated QoS calls for efficient scheduling and data transmission strategies.

However, a close look into the existing hybrid scheduling strategy for wireless systems reveals that most of the scheduling algorithms aims at minimizing the overall average access time of all the clients. We argue that this is not sufficient for future generation cellular wireless systems which will be providing QoS differentiation schemes. The items requested by clients having higher priorities might need to be transmitted in a fast and efficient manner, even if the item has accumulated less number of pending requests. Hence, if a scheduling considers only popularity, the requests of many important (premier) clients may remain unsatisfied, thereby resulting in dissatisfaction of such clients. As the dissatisfaction crosses the tolerance limit, the clients might switch the service provider. In the anatomy of today's competitive cellular market this is often termed as *churning*. This churning has adverse impacts on the wireless service providers. The more important the client is, the more adverse is the corresponding effect of churning. Thus, the service providers always want to reduce this churn-rate by satisfying the most important clients first. The data transmission and scheduling strategy for cellular wireless data networks thus needs to consider not only the probability of data items, but also the priorities of the clients.

1.4 Multichannel Scheduling

In order to improve the broadcast efficiency in asymmetric communications, one can divide the large bandwidth of the downlink channel in multiple disjoint physical channels. Then, for total push systems, the *Multiple Broadcast Problem* deals with finding the broadcast schedule on a multi-channel environment which minimizes the *Multiple Average Expected Delay*

(MAED), that is the mean of the Average Expected Delay measured over all channels a client can afford to listen. At the best of our knowledge, only total push schedules for multiple channels have been proposed so far. Such solutions may either transmit all data items on each channel or partition the data items in groups and transmit a group per channel. In the former case, MAED can be scaled up to the number of channels that clients can simultaneously listen by coordinating the solutions for each single channel. In the latter case, clients must afford to listen to all channels, but not necessarily simultaneously. When data items are partitioned among the channels, and the flat schedule is adopted to broadcast the subset of data assigned to each channel, the Multiple Broadcast Problem boils down to the *Allocation Problem* introduced in [12, 53]. For such a problem, the solution that minimizes MAED can be found in time polynomial in both the size of data and the number of channels [53, 54, 12]. However, the optimal schedule can only be computed *off-line* because it requires in input the data sorted by decreasing demand probabilities. Moreover, the strategy is *not dynamic* and the optimal solution has to be recomputed from scratch when the data demand probabilities change. Thus, a need for an efficient online, dynamic, multi-channel broadcast scheme arises.

1.5 Contribution and Scope of the Work

The prime objective of this thesis is to develop a framework for new hybrid scheduling strategy for heterogeneous, asymmetric environments. The hybrid scheduling needs to be adaptive and practical enough to be applicable in real-life systems. Subsequently, it should consider the effects of clients' requests as well as their importance to select a particular item for dissemination. More precisely, we can say that the contribution and the scope of the thesis are the following:

1. We first propose an ideal hybrid scheduling that effectively combines broadcasting of more popular (i.e., push) data and dissemination upon-request for less popular (i.e., pull data) in *asymmetric* (where asymmetry is arising for difference in number of clients and servers) environments. In this approach, the server continuously alternates between *one push item and one pull* operation. We have assumed an ideal system where the clients sends their requests to the server and waits for the necessary data item until they receive it. The data items are initially considered to be of uniform and unit-lengths. At any instant of time, the item to be broadcast is selected by applying a Packet Fair Scheduling (PFS). On the other hand the item to be pulled is the one selected from the pull-queue using Most Request First (MRF) scheduling principle.
2. Subsequently, we enhance the proposed hybrid scheduling scheme to incorporate the items having different lengths. While the push schedule is still based on PFS, the item to be pulled is the one selected from the pull-queue using *stretch optimal* (i.e, *max-request min-service-time first*) scheduling principle. We argue that stretch is a more practical and better measure in heterogeneous system, where items have variable lengths and the difference in item-lengths results in the difference in service time of data items. Hence, apart from the client-requests accumulated, the system also needs to consider the service time of the items as items of larger size should wait longer than items of shorter length. The performance of our hybrid scheduler is analyzed to derive the expected waiting time. The cut-off point between push and pull items is chosen so as to minimize the overall waiting time of the hybrid system.
3. Subsequently, the hybrid scheduling strategy is further improved so

that it does not combine one push and one pull in a static, sequential order. Instead, it combines the push and the pull strategies *probabilistically depending on the number of items present and their popularity*. In practical systems, the number of items in push and pull set can vary. For a system with more items in the push-set (pull-set) than the pull-set (push-set), it is more effective to perform multiple push (pull) operations before one pull (push) operation. We claim that our algorithm is the first work which introduces this concept in a dynamic manner. This has the power to change the push and pull lists on real time and to minimize the overall delay. A strategy for providing specific performance guarantee, based on the deadline imposed by the clients is also outlined.

4. In most practical systems, the clients often get impatient while waiting for the designated data item. After a tolerance limit, the client may depart from the system, thereby resulting in a drop of access requests. This behavior significantly affects the system performance, which needs to be properly addressed. Although an introduction of impatience is investigated in [24], the work considers only pure push scheduling. One major contribution of our work lies in minimizing the overall drop request as well as the expected waiting time.

There are also ambiguous cases which reflect the false situation of the system. Consider the scenario where a client gets impatient and sends multiple requests for a single data item to the server. Even if that particular data item is not requested by any other client, its access probability becomes higher. In existing systems, the server remains ignorant of this fact and thus considers the item as popular and inserts it into the push set or pull it at the expense of some other popular item. In contrast, our work reduces the overall waiting time of the

system in the presence of anomalies. More precisely, we develop two different performance models – one to incorporate clients’ impatience and the other to address anomaly-removal strategy – to analyze the average system behavior (overall expected waiting time) of our new hybrid scheduling mechanism.

5. One major novelty of our work lies in separating the clients into different classes and introducing the concept of a new selection criteria, termed as *importance factor*, by combining the clients’ priority and the *stretch* (i.e, *max-request min-service-time*) value. The item having the maximum importance factor is selected from the pull queue. We argue that this is a more practical and better measure in the system where different clients have different priorities and the items are of variable lengths. The service providers now provide different service level agreements (SLA), by guaranteeing different levels of resource provisioning to each class of clients. The QoS (delay and blocking) guarantee for different class of clients now becomes different, with the clients having maximum importance factor achieving the highest level of QoS guarantee. The performance of our heterogeneous hybrid scheduler is analyzed using suitable priority queues to derive the expected waiting time. The bandwidth of the wireless channels is distributed among the client-classes to minimize the request-blocking of highest priority clients. The cut-off point, used to segregate the push and pull items is efficiently chosen such that the overall costs associated in the system gets minimized. We argue that the strict guarantee of differentiated QoS, offered by our system, generates client-satisfaction, thereby reducing their churn-rate.
6. A new on-line hybrid solution for the Multiple Broadcast Problem is investigated. The new strategy first partitions the data items among

multiple channels in a balanced way. Then, a hybrid push-pull schedule is adopted for each single channel. Clients may request desired data through the uplink and go to listen to the channel where the data will be transmitted. In each channel, the push and pull sets are served in an interleaved way: one unit of time is dedicated to an item belonging to the push set; and one to an item of the pull set, if there are pending client-requests not yet served. The push set is served according to a flat schedule, while the pull set according to the Most Request First policy. No complete knowledge is required in advance of the entire data set or of the demand probabilities, and the schedule is designed on-line.

7. A considerable portion of this thesis is involved in performance analysis of the hybrid scheduling strategies. We have deeply investigated into the modeling of the scheduling schemes using suitable tools, like, *birth and death process* and *Markov Chain*. The major objective of this performance modeling is to get an estimate of the average behavior of our hybrid scheduling system. Extensive simulation experiments are also performed to corroborate the performance modeling and analysis. Simulation results as well as performance modeling point out the fact that a wise selection of cutoff-point to separate push and pull scheduling together with consideration of practical aspects like adaptive push-pull operations, clients' impatience and service classification has the capability to endow the system with better scheduling strategy, thereby improving the Quality of Service (QoS) of the system.

1.6 Organization of the Thesis

The overall thesis is organized as follows: Chapter 2 introduces the basic push-pull scheduling and also highlights the major existing works in push,

pull and hybrid scheduling. We have introduced our new hybrid scheduling scheme for homogeneous, unit-length items in Chapter 3. This chapter also extends the basic hybrid scheduling over heterogeneous (different-length) data items. In order to make the hybrid scheduling adaptive to the system load, Chapter 4 discusses the improvement over this hybrid scheduling and also outlines the basic performance guarantee offered by the hybrid scheduling scheme. The effects of clients' impatience, resulting in their departure from the system and transmission of spurious requests to create an anomalous system-behavior and its efficient solution is discussed in Chapter 5. A different modeling strategy and performance analysis using multi-dimensional Markov Chain is developed in Chapter ?? to get a better picture of the clients' retrials and repeated attempts. The concept of service classification in hybrid scheduling and its effects in providing a differentiated QoS is described in Chapter 7. We propose a new hybrid scheduling over multiple channels in Chapter 8. The dissertation concludes with pointers to future research works in Chapter 9.

Chapter 2

Related Work in Push-Pull Scheduling

Broadly all data transmission mechanisms can be divided into two parts: (1) push-based data broadcasting and (2) pull-based data dissemination. The origin of push-based data broadcasting arises from solving the asymmetry of wireless communication channels. In push-based systems, the server periodically broadcasts a set of data items to the set of all clients, without any client's intervention. The client's just listen to the down-link channel to obtain its required data items. Indeed, this saves bandwidth in the resource-constrained uplink wireless channels. On the other hand, in pull-based systems, a client uses the uplink channel to send explicit request for a particular data item to the server. The server, in turn, transmits the item to the client.

2.1 Push-based Systems

Push-based broadcast systems explore the downstream communication capacity of wireless channels to periodically broadcast the popular data items. Figure 2.1 demonstrates this basic push-based scheduling principle. The clients present in the system does not need to send explicit request to the

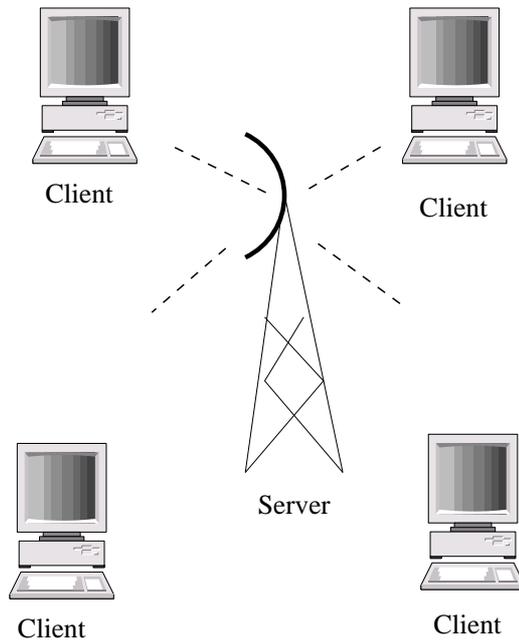


Figure 2.1: Push-based Broadcasting

server for any item, thereby saving the scarce upstream channel resources. Instead, the clients simply listen to server until it receives its desired data item. A wide variety of push-based broadcast scheduling exists in the literature. The vision of efficient push scheduling lies in effectively reducing the overall access time of the data items in asymmetric communication environment. The concept of broadcast disks, resolving dependencies among different broadcast data items, jitter approximation and introduction of fair scheduling have contributed to the eventual realization of this vision. Recent research trends have also addressed the issues related to broadcast of heterogeneous data items and polynomial costs. In this section we take a look into the different major existing push-based broadcast scheduling strategies.

2.1.1 Broadcast Disks for Asymmetric Communication

The concept of broadcast disk was first introduced in [1] to explore the downstream channel abundance in asymmetric communication environment. The key idea is that the server broadcasts all the data items to multiple clients. In such a push-based architecture, the broadcast channel essentially becomes a *disk* from which the clients retrieve the data items. The broadcast is created by assigning data items to different disks of varying sizes and speeds. Items stored in faster disks are broadcast more often than the items on the slower disks. Number of disks, their sizes and relative speeds can be adjusted to make the broadcast match the data access probabilities. Assuming a fixed number of clients with static access pattern for read-only data the objective of the work is to construct an efficient broadcast program to satisfy the clients' needs and manage the local data cache of the clients to maximize their performance. Intuitively, increasing the broadcast rate of one item decreases the broadcast rate of one or more items. With the increasing skewness of data access probabilities, the flat round-robin broadcast results in worse performance. Multi-disk broadcast programs performs better than skewed broadcasts (subsequent broadcasts of same page clustered together). It also aids in pre-fetching techniques, power savings and obtaining a suitable periodicity in the broadcast program. The proposed algorithm orders the pages from most popular to least popular ones. It then partitions the list of the pages into multiple ranges, where each range contains pages with similar access probabilities. These ranges are termed as disks. Now, it chooses the relative frequency of broadcast for each of the disks. Each disk is split into smaller units, termed chunks. The broadcast program is created by interleaving the chunks. Thus, the scheme essentially produces a periodic broadcast program with fixed inter-arrival times per page. Unused broadcast slots are used for

transmitting index information, updates, invalidation or extra broadcast of extremely important pages. Fast disks have more pages than the slower ones.

2.1.2 Paging in Broadcast Disks

Similar to the concept of virtual memory, paging is also used in broadcast disks to improve its performance. However, a page-fault in broadcast disk has variable cost, which is dependent on the requested page as well as current broadcast state. Also pre-fetching a page is a natural strategy for performance improvement in broadcast paging. For n data items and a client's cache-size of k , a deterministic algorithm for achieving a $O(n \log k)$ competitiveness in broadcast paging is proposed in [26]. It also points out that in a system without any pre-fetching, no deterministic algorithm can achieve a competitive ratio better than $\Omega(nk)$. An algorithm is called *lazy* if it moves only when it misses and positions itself on the requested page. Such a lazy algorithm might load a page even if its is not requested as long as no time is spent waiting for that page. A request sequence is *hard* if it faults for every request in the sequence. Comparing the online broadcast paging algorithm \mathcal{G} with *lazy adversaries* reveals that the online algorithm ignores all requests that do not cause any fault and is c -competitive on all hard sequences on all such hard sequences. If n and k represent maximum number of pages in the system and maximum size of client-cache, then for $n = k + 1$, there exists a 1-competitive deterministic algorithm for broadcast disk paging. The competitive-ratio for a c -competitive deterministic algorithm is $(c - 1)n + 1$. In fact, without pre-fetching, no deterministic online algorithm can have a better competitive ratio than $\Omega(nk)$. This result is extended to incorporate randomized algorithms also, with the the bound being $\Omega(n \log k)$. A new broadcast paging algorithm, termed as *Gray algorithm* is proposed which uses a set of three marks, black, gray and white

and maintains a mark for each page. It has been shown that for a total number of w requests, the cost on the gray requests in a given segment is at most $O(wn \log k)$. This leads to the result that the amortized cost of algorithm Gray on white requests is $O(wn \log k)$. Hence, the algorithm is $O(n \log k)$ competitive and can be implemented by keeping track of $O(k)$ gray pages.

2.1.3 Polynomial Approximation Scheme for Data Broadcast

The first polynomial-time approximation scheme for data broadcast problem with unit length data items and bounded costs is introduced in [25]. The objective is to minimize the cost of the schedule, where the cost is actually consisted of *expected response time* and *broadcast cost* of the messages. The basic idea is to form different groups consisting of equivalent messages (i.e., messages having same cost and probability). Within every group these messages are rearranged in such a manner that they can be scheduled in a cyclic, round-robin fashion. This concept is extended to a generalized case of broadcast scheduling. A randomized algorithm is introduced which rounds the probabilities and costs of messages and partitions them into three similar groups. Subsequently a greedy technique is also introduced which minimizes the expected cost of the already allocated slots. This greedy schedule is at least as good as the randomized schedule. The period of this greedy technique is bounded in polynomial length.

2.1.4 Packet Fair Scheduling

The work of Hameed and Vaidya [19, 49] relates the problem of broadcast scheduling with *packet fair scheduling* (PFS) and subsequently present a $O(\log D)$ scheduling algorithm for D number of data items. It introduces the concept of *spacing* between two items as the time taken between

two consecutive broadcasts of a particular (same) data item. For optimal scheduling, any data item needs to be *equally spaced* [19, 49]. If, l_i and s_i represents the length and spacing of item i , then assuming a Poisson arrival of client requests, the waiting time of any client for that particular item is given by: $t_i = s_i/2$. Now, if p_i represents the probability of the item i , then the *overall mean access time* ($t_{overall}$) is given by $t_{overall} = \sum_{i=1}^D p_i t_i = \frac{1}{2} \sum_{i=1}^D p_i s_i$. At this point of time one needs a suitable, optimal expression of spacing s_i . If instances of all items are equally spaced, then, minimum overall access time is achieved when s_i and $t_{optimal}$ is given by the following equations:

$$s_i = \left[\sum_{j=1}^D \sqrt{p_j l_j} \right] \sqrt{\frac{l_i}{p_i}} \quad (a)$$

$$t_{optimal} = \frac{1}{2} \left[\sum_{i=1}^D \sqrt{p_i l_i} \right]^2 \quad (b) \quad (2.1)$$

Although, equal-spacing of data items is not always feasible in practical systems, $t_{optimal}$ provides a *lower bound* on the overall minimum expected access time. Packet fair scheduling algorithms essentially considers as switch connecting many input queues with a single output queue. The objective is to determine which packet will be transmitted from the set of input queues to the output queue. For a specific value ϕ_i , the input queue i should get at least fraction ϕ_i of the output bandwidth. Thus bandwidth is *evenly distributed* between the input queues. Since, for optimal scheduling the spacing between consecutive instances of same data item i needs to be obtained from Equation 2.1(a). Thus we have,

$$\frac{l_i}{s_i} = \frac{l_i}{\left(\sum_{j=1}^D \sqrt{p_j l_j} \right) \sqrt{l_i/p_i}} = \frac{p_i l_i}{\sum_{j=1}^D \sqrt{p_j l_j}} \quad (2.2)$$

The performance of the algorithm can be further improved by using suitable bucketing techniques [49]. However, wireless channels are inherently

lossy and error-prone. Thus any practical broadcast scheduling should consider the associated transmission errors. While error control codes (ECC) aids to correct these errors, it is not possible to correct all the errors. Any erroneous packet is discarded after reception.

2.1.5 Broadcasting Multiple Data Items

Traditional broadcasting schemes, which do not consider the relationship between these data items often increases the average access time to process clients' requests in this environment. The problem of deciding and scheduling the content of the broadcast channel is found to be NP-hard [29]. Subsequently different greedy heuristics exist for obtaining near-optimal solutions.

Intuitively it is quite clear that the deciding the content of the broadcast channels is based on the *clients' queries*. Given a set of queries and a set of equal-sized data items, each query accesses a set of data items termed *query data set*. For a given set of data items and queries, the query selection problem is to choose a set of queries, which maximizes the total overall frequency of queries, constrained to the number of data items over all queries to be bounded by maximum possible number of data items currently present in the channel. Three different greedy approaches based on (i) *highest frequency*, (ii) *highest frequency/size ratio* and (iii) *highest frequency/size ratio with overlapping* are proposed to solve this query selection problem.

The proposed query expansion method sorts the query according to their corresponding access frequencies and inserts the data items of each query in a greedy manner. Higher frequency queries are given higher preferences for expansion. This basic method is extended to include the frequencies of data items also. In order to reduce the overall access time, the query-set of the overlapping and previously expanded data items are modified by

moving the data items to either left-most or right-most positions of the previous schedule. This change makes the data items adjacent to data items of currently expanded query. The moving of queries is performed only if the remaining queries benefitted from this operation is larger than the remaining queries that suffer from this operation. On the other hand, the content of the scheduling can be expanded on the basis of data items also. The data items of chosen queries are transformed to a *data access graph* – a weighted, un-directed graph. Each vertex represents a certain data item and each edge represents that the two data items belonging to a certain query. The procedure combines two adjacent vertices of the graph into a *multi-vertex*. If any vertex has more than one edge to a multi-vertex, the edges are coalesced into a single edge with the previous edge-weights added to form the total new weight. The procedure is iterated until the graph is left with a single multi-vertex.

2.1.6 Broadcasting Data Items with Dependencies

Researches have demonstrated the existence of a *simple optimal schedule* [7] for two files. Considering all possible combinations of clients from both the classes and accessing the data items of any single or both the classes, the work has shown that for equal length files with no dependencies *any optimal schedule can be partitioned into consistent simple segments*, i.e., there exists an optimal simple schedule. The model is also extended to incorporate variable length file sizes. But it has been proved that a simple, optimal schedule still exists.

While the objective of broadcast schedule is to minimize the access cost of a random client, most of the schedules are based on the assumption that access cost is directly proportional to the waiting time. However, in real scenarios the *patience* of a client is often not necessarily proportional to the waiting time. This makes the broadcast scheduling problem even more

challenging by generating polynomial cost functions.

2.1.7 Broadcast Schedule with Polynomial Cost Functions

Recent researches [10] have shown the formulation of *fractional modelling* and *asymptotically optimal* algorithms for designing broadcast schedules having cost functions arbitrary polynomials of client's waiting time. For any data item $i \in \{1, 2, 3, \dots, D\}$ with probability p_i a cyclic schedule is a repeated finite segment. For any increasing cost function the optimal fractional broadcast schedule with minimum expected cost results when successive instances of each data item are equally spaced. For such a model, the optimality is achieved when the frequency of each item satisfies the relation: $frequency_i = \frac{\sqrt{p_i}}{\sum_{j=1}^D \sqrt{p_j}}$. The access probabilities of the data items are assumed to obey Zipf distribution, with access skew coefficient θ . Subsequently a random algorithm, a halving algorithm, a fibonacci algorithm and a greedy algorithm is proposed to obtain the optimal fractional schedule.

1. At each step, the random algorithm transmits a page such that expected frequency of each page approaches exact frequency of fractional schedule. For linear (first order) function, random algorithm provides a solution bounded by *twice* the optimal cost. However, the performance of the random algorithm deteriorates exponentially for non-linear function.
2. Halving algorithm attempts to achieve the optimal fractional schedule by rounding off the desired page frequencies to nearest power of $1/2$. When the desired frequencies are always powers of 2 the strategy achieves the optimal schedule. On the other hand, in the worst case, the actual frequency is always more than $1/2$ the original frequency.

For linear cost model, the halving algorithm results in costs bounded by twice the optimal algorithm.

3. Like random algorithm fibonacci (golden ratio) algorithm also generates schedule with same average frequencies as those of the optimal fractional solution. However, the spacing between two consecutive appearances of same item in the schedule may have three different schedules close to the optimal periods. For a linear cost function, the fibonacci algorithm generates a schedule whose cost is $9/8$ times the cost of optimal fractional model.
4. At every step the greedy algorithm broadcasts the item which will be having maximum cost if not broadcasted. A finite schedule is computed and repeated at each iteration of the algorithm. Even with exponential cost function, the greedy approach results in a very near optimal solution.

2.1.8 Jitter Approximation Strategies in Periodic Scheduling

Perfectly periodic scheduling broadcasts each item at exact time intervals. This removes the constraint for the client to wait and listen to the server until its desired item is broadcasted. Instead, the client now has the flexibility to switch its mobile on exactly when needed, thereby saving the energy of power-constrained hand-held mobile terminals. Jitter is estimated as the difference in spacing between the consecutive occurrences of the same data item. A new algorithm for controlling the jitter in the schedule is proposed. It requires that the ratio between any two periods to be a power of 2. The key idea is to evenly spread the schedule over the entire period in a recursive fashion. Idle slots are inserted in the schedule to remove the imperfect balancing. Using a suitable parameter the algorithm controls the influence of jitter and period approximation. It first constructs a binary

tree to create a replica for each job in the instance and associates these replicas with the root of the tree. Each node has exactly two children. In order to ensure low jitter, the strategy uses a total ordering of jobs. This results in reduction of the jitter in databroadcasting.

2.1.9 Dynamic Levelling for Adaptive Data Broadcasting

The major important problem associated with this research on broadcasting over multiple channels lie in generating hierarchical broadcast programs with a given number of data access frequencies and a number of broadcast disks in a broadcast disk array. The problem of generating hierarchical broadcast programs is first mapped into construction of channel allocation tree with variant fan out [33]. The depth of the allocation trees corresponds to the number of broadcast disks and the leaves in the same level actually represents the specific data items. The data items in the fast disks are faster accessible than the data items in slower disks. However, the data access frequencies change over time. The broadcast programs need to dynamically adapt to all such changes.

2.2 Pull-based Systems

While push-based broadcast strategy attempts to reduce the overall expected access time, it suffers from two major disadvantages:

1. The server broadcast does not discriminate between the popular (hot) and non-popular (cold) items. Thus, the non-popular (cold) items are also broadcasted repeated times in periodic intervals. This results in wastage of valuable bandwidth, because the non-popular items are required by a few, handful of clients.
2. On an average the overall expected access time becomes half of the

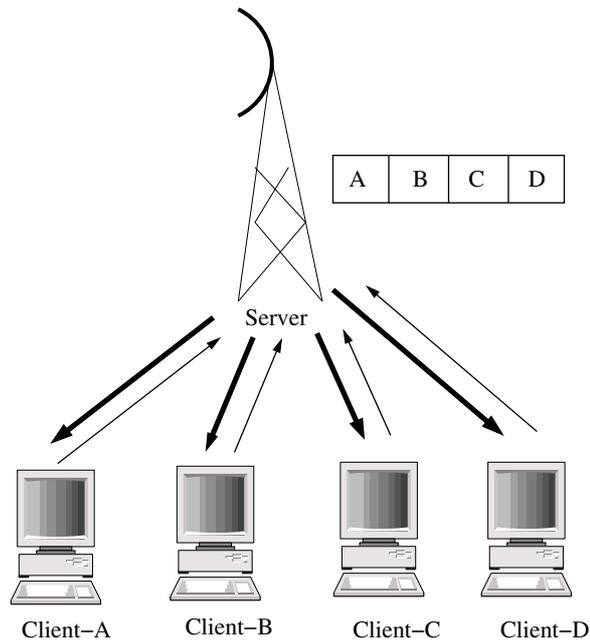


Figure 2.2: Pull-based Data Dissemination

entire broadcast cycle length. Hence, for a system having very large number of items, some of which are non-popular, the average waiting time for the popular items also becomes pretty high. In other words, the popular items suffer for the presence of non-popular items.

A close look into the scenario reveals that the major reason behind these two problems lie in the absence of clients' explicit role in the scheduling. Indeed, push-based scheduling does not take the clients' need into account. This gives rise to the on-demand pull scheduling. Figure 2.2 shows the basic of on-demand pull scheduling. In pull-based data transmission scheme, the clients explicitly send uplink request for a particular data item to the server. The server, in turn, process the requests and transmits the data item over down-link channel. A wide variety of scheduling principles exist for this pull-based scheduling. While most request first (MRF) provides a low average access time, it suffers from fairness. On the other hand, first-come-first-serve (FCFS), is fair, but suffers from sub-optimality and

increased average access time. A combination and modification of these basic scheduling principles give rise to other scheduling like, shortest time first (STF) and lowest waiting time first (LWTF). Subsequently, caching, pre-fetching and opportunistic scheduling is also used to improve the performance of on-demand pull-based data transmission. The eventual goal is to satisfy certain timing constraints imposed by real-time communication. In this section we take a look into the major pull-based scheduling strategies.

2.2.1 On-demand Data Dissemination

The scheduling problems arising in on-demand broadcast environments for applications with heterogeneous data items is investigated in [3]. A new metric *stretch* is introduced for performance measurement in heterogeneous environments. The primary objective of the proposed algorithm is to optimize the *worst case stretch* of individual requests. Like other pull-based applications, the clients send explicit requests to the server and the server transmits the specific item to the client. The transmission unit is page – a basic fixed-length unit of data transfer between clients and server. The pages are assumed to have self-identifying headers, which are delivered in a specific order. The concept of preemption is used to achieve better scheduling performance. This also aids in implementing the the scheduling strategy with less complexity, as most of the non-preemptive scheduling schemes are *NP-hard*. The preemption helps in avoiding the backlog of pending requests when a long job is being serviced. Preemption of an item for a more popular item also has the potential for the improvement of its performance. While response time is the most popular performance measure, it is not a fair measure in heterogeneous systems. Individual requests differ in terms of their service time. The proposed strategy uses the concept of *stretch*, defined as *the ratio of response time of a request*

to its service time. Stretch explores the intuitive concept that larger jobs should take more service time than the smaller jobs. The jobs are classified into different classes based on their service times. The *average of maximum stretch for each class (AMAX)* aids to get the overall picture of the entire system. This classification helps in better understanding of the system performance. This algorithm repeatedly guesses a stretch-value, which immediately yields a *deadline* for each job based on its arrival and service time. Earliest deadline first (EDF) is used to determine if all jobs can be scheduled with a bounded maximum stretch-value, thereby meeting the respective deadlines. The objective is to use the past access-history to make intelligent guess of stretch-values. The current stretch is used to obtain the deadline.

2.2.2 RxW Scheduling

The *RxW* algorithm in [4, 5] is proposed to meet these criteria. By making the scheduling decisions based on current request queue state, *RxW* can adapt to the changes in client population and workload.

The primary intuition behind designing the *RxW* algorithm is to exploit the advantages of both MRF and FCFS. While MRF provides lowest waiting time for popular pages, it suffers from fairness and might lead to starvation of non-popular requests. On the other hand, FCFS is fair but suffers from higher waiting time. The success of LWF lies in providing more bandwidth to popular pages, while avoiding starvation of non-popular pages. *RxW* combines the benefits of both MRF and FCFS in order to provide good performance to both popular and non-popular items, while ensuring scalability and low overhead. Intuitively, it broadcasts every page having the maximal $R \times W$ values, where R and W are the number of pending requests and time of the *oldest outstanding request* for the particular page. Three different versions of the *RxW* algorithm is proposed:

1. *Exhaustive $R \times W$* : The exhaustive $R \times W$ maintains a structure containing a single entry for each page having outstanding requests. It also maintains R , 1st arrival time. For any arriving request, a hash look up is performed to get the page. If the request is the first one, then the R is initialized to 1 and 1st arrival is initialized to current time; otherwise the value of R is incremented. The server selects the page having largest $R \times W$ value.
2. *Pruning Search Space*: This version of the algorithm uses two sorted lists (i) the W -list, ordered by increasing order of 1st arrival time and (ii) the R -list, ordered by decreasing order of R -values. The entries in the W -list are kept fixed until the page is broadcasted. However, the entries in the R -list is changed during every request arrival. This makes request processing a constant-time operation. The pruning scheme truncates the W -list. The algorithm alternates between two lists, updating the maximum value of $R \times W$ at every iteration.
3. *Approximating $R \times W$* : The approximated, parameterized version of $R \times W$ reduces the search space even further at the cost of suboptimal broadcast decision. For highly skewness data items, the maximal $R \times W$ values is obtained at the beginning of the least one of the two lists. Also, the static workload, the average $R \times W$ value of the page chosen to be broadcast converges to a constant.

2.2.3 Data Staging for On-Demand Broadcast

The $R \times W$ algorithm [4, 5], discussed before, is extended to incorporate these data staging strategies [6] for improved performance of on-demand data broadcasting. The server maintains a service queue for keeping the outstanding clients' requests. Upon receiving a request, the queue is checked. If the item is already present, then the entry is updates, otherwise a new

entry for that item is created. An ending is also kept to track the items for which an asynchronous fetch request is pending. The limit of this request is constrained by the size of the pending list. The server first checks for completion of any asynchronous fetches in the pending list. The items arrived by fetch operation are broadcasted in the order they were received and the corresponding entries are removed from the pending list. If the pending list is not full, the server operates in *normal mode*, otherwise, it operates in *opportunistic mode*. In the normal mode, the server selects an item using *RxW* algorithm. If the selected item is found in cache, it is broadcasted, otherwise an entry to the item is created in pending list and request for the item is sent to the remote site or secondary/tertiary item. When the server has reached the limit of outstanding requests, the system switches to opportunistic scheduling mode. The algorithm is now restricted to cache-resident pages, having at least one pending requests. A single bit in the service queue is kept to check whether the page is cache-resident or not. The algorithm now attempts to find the best available (cache resident) page according to *RxW* strategy. A new modified LRU replacement scheme, termed as *LRU with love/hate hint* (LRU-LH) is used to improve the cache replacement strategy. The popular and non-popular pages are marked as ‘love’ and ‘hate’ to put them in the up and bottom of the LRU chain. A page is selected for broadcast if it is encountered on the *R*-list before *W*-list.

2.2.4 Pull Scheduling with Timing Constraints

An investigation into traditional realtime non-mobile and non-realtime mobile data transmission strategies is performed in [15]. Subsequently an efficient pull-based scheduling scheme based on *Aggregated Critical Requests (ACR)* is designed to meet the specific deadline of clients’ requests.

In realtime non-mobile environment, the server assigns priorities to

transactions based on several strategies, like, Earliest Deadline First (EDF) or Least Slack (LS) first. As the name suggests, in EDF the item with earliest deadline is given the highest priority. On the other hand, in LS the slack time at any instant t is estimated as: $deadline - (t + executionTime - processorTime)$. The transaction is capable of meeting the deadline if the slack time is zero. Although EDF is the best overall strategy, it performs in a very poor manner when the system load is high. In pull-based, mobile non-realtime strategies, the Longest Wait First (LWF) often outperforms all other schemes to achieve the minimum waiting time. LWF computes the sum of total time that all pending requests have been waiting for a data item. The database is assumed to consist of a fixed number of uniform pages, where each page fits into one slot. Broadcast time of each page is equal to 1 slot. Assuming an Poisson arrival rate, the system assigns the slots to particular data items such that the *long term deadline miss ratio* is minimized. At any time slot t this ACR strategy attempts to minimize the deadlines missed during time slot $t + 1$ by transmitting the page with the most deadlines to meet before slot $t + 1$. The waiting requests are kept in the pull queue. The server maintains the number of deadlines to be missed if a page is not transmitted in the next time slot. The requests corresponding to the deadlines are termed as *critical requests* and the server updates the number of critical requests for the data item at every time slot. It chooses the page having largest number of critical requests to transmit, delete the requests with missed deadlines and reset the number of critical requests.

2.2.5 Scheduling with Largest Delay Cost First

While most broadcast scheduling strategies (both adaptive and non-adaptive) attempt to minimize the overall access time, recent researches have been focussed to reduce the overall delay cost [46] in on-demand pull based data

dissemination schemes. The delay cost consists of three different components. Apart from the existing overall access time cost it also takes the tuning time costs and failure recovery costs into account. Like conventional pull scheduling schemes, in the proposed *largest delay cost first* (LDCF) the clients explicitly send the request for specific data items to the server. However, it does not wait indefinitely for server's response. Instead, the clients use a *response time limit* (RTL) to indicate the maximum possible time it can wait for server's response. The strategy also considers *tuning time costs*, which corresponds to the search for the location of a particular data item in the index. During the entire broadcast period, the strategy receives the new requests and add them into the request sequence. The data item with largest priority is selected and added to the broadcast period, sorted by the descending order of popularity factor. The index is obtained and data item is broadcasted. The failure requests are now cleared.

2.3 Both Push and Pull

At this point of time, it is clear that both push-based and pull-based scheduling have some specific advantages. Naturally, a wise approach is to explore the advantages of both of these basic data transmission mechanisms. This gives rise to some interesting data transmission schemes, like, *lazy data request*.

2.3.1 Lazy Data Request for On-demand Broadcasting

While the prime goal of data broadcasting is reducing the overall access time, most practical systems need to consider the messaging overhead also. On the other hand, the load of the real-time systems often change in a dynamic fashion. Hence, the broadcast system needs to be robust enough to adapt itself online with the system dynamics. The basic motivation

behind the lazy data request strategy [31] is to not to send the request for the data item but wait. The particular data item might already be broadcasted due to explicit request by other clients. This will result in saving of message passing in the uplink channel and battery power of the mobile terminal. It proposes a new *dynamic bounded waiting* strategy which contains two parts in the schedule: index section and data section. The client can use the index section to get an predicted estimate of the item to be broadcasted in near future. The server chooses *a set of data items* and the items are *batched together* for broadcasted. The corresponding index section is broadcasted before the transmission of the batch set. The number of items to broadcast in a batch set is determined by a control variable termed *selection factor*. In the worst case the client tunes at the beginning of a data section and waits till the end of next index section of the next data set.

2.4 Hybrid Scheduling

Hybrid approaches, that use the flavors of both push-based and the pull-based scheduling algorithms in one system, appears to be more attractive. The key idea is to separate the data items into two sets: (1) popular and (2) non-popular. While the popular data items are broadcasted using push-based transmission strategy, the relatively non-popular items are transmitted using on-demand pull-based scheduling strategy. A suitable balance between push and pull scheme is of utmost important at this aspect. A major characteristic of an efficient hybrid scheduling strategy is its adaptiveness. The strategy should be able to change the scheduling decisions online. In this section we will look into the major hybrid scheduling techniques.

2.4.1 Balancing Push and Pull

The work of Acharya, Franklin and Zdonik [2] is perhaps the first significant work which effectively explores the advantages of both push and pull based data transmission strategies. The work introduces the asymmetry in different factors, like, (i) uplink and downlink channels (ii) clients and server ratio (iii) amount of data downloaded and uploaded. The proposed strategy considers a capacity-constrained server and multiple clients with uplink channels. It then extends the static, push-based data broadcasting to incorporate pull-based on-demand data transmission schemes for read-only data items. For push based broadcast scheduling, the proposed algorithm, selects the cached page which contains lowest p/x ratio. The pull-based on-demand scheduling is modeled as a *point-to-point* connection with the server. While the rate of client-requests increases with number of clients, the server has a constraint of maximum allowable requests it can handle. The server is capable of interleaving push and pull-based data items, and options are kept to vary the percentage of slots dedicated for on-demand pull scheduling. The requests are accumulated and kept in the pull-queue. The server selects the item in a first-come-first-serve (FIFO) fashion. A threshold parameter is kept to maintain the use of back-channel under certain limits. While Measured Client models a single client, the Virtual Client models the combined effect of all other clients in the system. It maintains a cache holding different pages and waits for certain time units between two consecutive requests. If possible the requests are serviced from the cache, otherwise, they are broadcasted or pulled.

2.4.2 On-Demand Broadcast for Efficient Data Dissemination

A demand-driven broadcast framework, termed *Broadcast on Demand (BoD)* is proposed in [52], which satisfies the temporal constraints of the requests

and uses scheduling techniques at the server side to dynamically utilize the limited bandwidth. The framework allows mobile clients limited ability to transmit queries to the server with the maximum tolerable latency. The server is capable of producing a broadcast which satisfies the clients' requests and retains scalability and bandwidth utilization. Essentially the broadcast communication is combined with on-demand data dissemination. It customizes the broadcast service to service individual clients better, while avoiding the scalability problem of client/server model. Time division multiplexing is used to utilize a fraction of the bandwidth for periodic broadcast and the rest for on-demand data transmission.

The broadcast strategy uses *earliest deadline first (EDF)* to schedule the transmission of data items. In the planning-based non-preemptive broadcast strategy, a sorted target-set of the number of requests need to be broadcast is formed. At every iteration an item, having the closest deadline is chosen from the target. However, this schedule often performs poorly in overload situation. This is solved by using batching of multiple information and handling the batched requests by a single transmission of data items. Unlike EDF, for every transmission request EDF-BATCH checks if that transmission is already planned. If so, it does not re-transmit the data as the planned transmission will take care of that data, otherwise the scheduler attempt to transmit the data. This results in bandwidth savings with less overhead. This strategy is extended to make the scheduling hybrid by incorporating on-demand pull-based scheduling schemes. On arrival of a client's request, first the server checks if periodic broadcast can satisfy the request within deadline. If so, no on-demand scheduling is needed; otherwise, the on-demand scheduling is used.

2.4.3 Channel Allocation for Data Dissemination

A different dynamic channel allocation method, which assigns channels for broadcast or on-demand services based on system workload is discussed in [27, 20, 28]. The proposed channel allocation algorithm efficiently achieves the optimal channel allocation by approximation techniques. The wireless communication platform is assumed to be supported by a Mobile Support Station (MSS). Every cell is assumed to be consisted of one MSS and multiple mobile computers. The MSS maintains D data items and the mobile computers issue requests to the MSS. Using the concept of a $M/M/c/n$ queuing model (with finite buffers) the expected access time ($E[PULL]$) of on-demand system under heavy load is approximated. Similarly for broadcast channels a cost analysis is performed and the expected access time for retrieving data through monitoring the broadcast channel is obtained. In order to achieve optimal data access efficiency in the cells, the system dynamically reassigns channels between on-demand and broadcast services. The allocation algorithm starts with exclusive on-demand system (i.e., broadcast set being empty). It then initializes the lowest access time depending on whether the system is heavily or lightly loaded. Now at every iteration the algorithm identifies the data items to be transmitted. Then it computes the channel allocation policies and obtain the optimal allocation by choosing the policy which minimizes the overall access time. This scheme is performed both in heavy and light load.

2.4.4 Wireless Hierarchical Data Dissemination System

A hierarchical data delivery (HDD) model is proposed in [21] which integrates data caching, information broadcasting and point-to-point data delivery schemes. The broadcast schedule and cache management schemes are dynamically adjusted to minimize the overall access time. Efficient data

indexing methods are also explored in this environment. Data are stored in the hierarchies, with most requested data in client-cache, followed by commonly used data in broadcast channel and least popular data in the server (for pulling). When a user issues a query the item is first searched in the cache. The item is retrieved if it is found in the cache, otherwise the item is searched in the server. If it is found within the threshold of the server's broadcast channel, it is obtained and kept in the cache; otherwise it is explicitly pulled from the server. The clients can explicitly issue signature to the broadcast channels. The model is formed using a single server and multiple clients. The client model is used to generate query with Zipf's and Gaussian distribution, broadcast channel monitoring and request for pull items. The server model uses broadcast disk management techniques to schedule data items in an efficient manner.

2.4.5 Adaptive Hybrid Data Delivery

An adaptive hybrid data delivery strategy is also proposed in [32], which dynamically determines the popularity of the data items and effectively combines the push and pull based strategies. In other words, the data items are neither characterized nor predicted a-priori. The continuously adjusts the amount of bandwidth to match the diverse demand patterns of the clients. The total bandwidth is logically distributed into three parts for (1) broadcasting index block, (2) broadcasting data blocks and (3) unicasting on-demand data blocks. The distribution adapts with the changes in clients' demands. The system begins with server broadcasting one or more index or data objects. Increasing number of requests for a particular data will increase the bandwidth allocation for that data item and vice-versa. One major advantage of this approach is that it implicitly takes care of the fact that when the requests for a data item is reduced due to the satisfaction of the clients recently received that data item. The server

then reduces the bandwidth allocation for that data item. However, subsequent requests by the set of clients for that same data item increases the popularity of that item, and the server re-assigns more bandwidth for that particular data item. One prime objective of the work is to minimize the overall access time, where the access time is composed of access time for index, tuning time and access time for data.

2.4.6 Adaptive Realtime bandwidth Allocation

The real-time data delivery strategy discussed in [30] maintains a certain level of on-demand request arrival rate to get a close approximation of optimal system response time. One advantage of the system is that it does not explicitly need to know the access information of the data items. A single broadcast channel and a set of on-demand point-to-point channels are used in a single cell environment. The data items are of uniform size and the number of data items in the broadcast channel changes with variation in the system load. The clients first listen to the broadcast channels for respective data items they are waiting for. Only if the required data item is not found, the client transmits explicit request to the server for that particular data item. A MFA (bit) vector and a broadcast number is kept. Each bit in the vector represents a data item in the broadcast channel. Whenever a request is satisfied, the corresponding bit in the vector is set. The server maintains a broadcast version number to ensure the validity of the relationship between bit-positions and data items. This vector and broadcast version number is piggy-backed to the server along with the on-demand data request. The server uses this information to update the request information available and get an almost accurate information regarding the clients' requests and data items received.

2.4.7 Adaptive Dissemination in Time-Critical Environments

An adaptive, online, hybrid scheduling and data transmission schemes for minimizing the number of deadlines missed is also proposed in [16]. The information server dynamically adapts to the specific data items that needs to be periodically broadcast and the amount of bandwidth assigned to each transmission mode. A *time critical adaptive hybrid broadcast* (TC-AHB) is proposed in which combines both periodic broadcast and on-demand dissemination efficiently. In this scheme both the data items being broadcast and the amount of bandwidth assigned dynamically changes in a per-cycle basis to adapt to the clients' needs. The decision regarding periodic broadcast and on-demand transmission is dependent on the access frequency. The amount of bandwidth assigned, on the other hand, is related to the deadline constraints. The server always computes periodic broadcast program for next cycle and leaves some bandwidth for on-demand transmission. The broadcast frequency is the minimum needed to satisfy the deadline constraints of the specific data items. An online scheduling policy is used to prioritize the requests according to their deadlines and subsequently minimize the number of deadlines missed. The server broadcasts the items which have high access requests and low bandwidth requirement. In each broadcast cycle it includes the data item which aids in maximum bandwidth savings. This process is continued until some bandwidth is left for on-demand transmission. Such a greedy strategy offers a solution which is very close to optimal solution. The on-demand scheduling used Earliest Deadline First (EDF), which is implemented using priority queues where priorities are inversely proportional to deadlines.

2.4.8 Adaptive Scheduling with Loan-based Feedback Control

In order to solve the dynamic information transmission problem, the work in [22] proposed a strategy to subsume the dynamic and static information into groups and introduce a loan-based slot allocation and feedback control scheme to effectively allocate the required bandwidth. A uniform building block, termed as a group, is designed. Every block has a unique Group-Id (GID). Two types of groups, namely, virtual and actual groups are formed. Clients interested for a static data item forms the virtual group. The server broadcasts the static items to the group at the same time. On the other hand, the actual group consists of the clients requesting dynamic data items. The server allocates a specific number of slots to each group depending on the particular group-popularity.

The dynamics of traffic might lead to excess of scarce slots (bandwidth) to the groups. A loan based slot allocation and feedback control (LSAF) scheme is introduced to complement the GID mechanism. At the start of a broadcast cycle, every group is assigned with a slot-quota. The server then performs dynamic slot allocation among the groups during a broadcast cycle. When the slot-quota of a particular group is exhausted (due to transmission of different data items belonging to that group), the server attempts to *loan* a slot from another group to broadcast any data item belonging to the previous group. This loan for slots is determined by any one of the three schemes: (1) *sensitive loan*: the server estimates and predicts the slot requirements of every group and loans a slot from the group, which will be having largest remaining slots in future; (2) *insensitive loan*: the server loans the slot from the group currently having largest unused slots normalized by the slot quota; (3) *greedy loan*: the server takes the loan from the group having largest remaining slots at current instant. At the end of each broadcast cycle the server estimates

and learns the amount of slots taken to deliver all group-specific items of any group by a direct feedback mechanism. This feedback mechanism essentially gives the required slot-quota to meet the specific group's need. This also gives an estimate of dynamic item production and transmission rate. In order to meet the real-time constraints, the server also delivers the queued items using a pull-scheduling and has the capability of preempting the slots in the next broadcast cycle and broadcasts the queued items using a push scheduling.

2.4.9 Framework for Scalable Dissemination-Based Systems

A general framework for describing and constructing Dissemination Based Information Systems (DBIS) is described in [14]. A number of data delivery mechanisms and investigate the tradeoffs among them. By combining various data delivery techniques the most efficient use available server and communication resources, the scalability and performance of dissemination-oriented applications is enhanced.

The approach distinguishes between three types of nodes: (1) *data sources* provide base data for application (2) *clients* consume this information and (3) *information broker* adds value to information and redistribute it. Information brokers binds the different modes of data delivery and drive the scheduling to select a particular mode, depending on its access patterns. Brokers provide network transparency to the clients. Brokers can be the data sources also. Data can be cached at any of the many points along the data path from the server to the client. Cache invalidations and refresh messages need to be send to each client cache manager. LRU or some other cache replacement policy can be used in this approach. Intermediate nodes can simply pass/propagate the data or can also perform some computations over those data. Provisions are also kept to recover some nodes from failure. The server relies on the clients' profile to optimize the push sched-

ule. The framework provides techniques for delivering data in wide-area network settings in which nodes and links reflect extreme variation in their operating parameters. By adjusting the data delivery mechanism to match these characteristics high performance and scalability can be achieved. The toolkit provides a set of classes to allow distributed nodes to negotiate in order to establish a connection and local cache. The data transmission policies needs to be agreed upon between the server and the clients.

2.4.10 Guaranteed Consistency and Currency in Read-Only Data

In order to ensure various degrees of data consistency and currency for read-only transactions, various new isolation levels are proposed in [44]. Efficient implementation of these isolation levels are also proposed. This is used in hybrid data transmission environment. The newly proposed consistency levels are independent of the existing concurrency protocols.

Although, serializability is standard criteria for transaction processing in both stationary and mobile computing, it is in itself not sufficient for preventing read-only transactions from experiencing anomalies related to data currency. A start-time multi-version serialization graph (ST-MVSG) is a directed graph with nodes = $commit(MVH)$ and edges E such that there is an edge representing every arbitrary dependency. Let MVH be a multi-version history over a set of committed transactions. Then MVH is BOT serializable if ST-MVSG is acyclic. In a MVH that contains a set of read-write transactions such that all read-write transactions are serializable, each read-only transaction satisfying READ-RULE is also serializable. This leads to the conclusion that MVH is strict forward BOT serializable if SFR-MVSG is serializable. In a multi-version history containing a set of read-write transactions such that all read-write transactions are serializable, each read-only transaction is serializable with respect to transactions belonging to the corresponding update. Simulation results

demonstrate that this improves the throughput control and number of abort associated in transactions.

2.4.11 Broadcast in Wireless Networks With User Retrials

Most of the research works in data broadcast do not consider the possibility of a single user making multiple request submission attempts. Such *retrial* phenomenon has significant attempt on the system's overall performance. The prime objective of the work in [50] is to capture and analyze the *user retrial phenomenon* in wireless data broadcast schemes. The objective is realized by introducing different performance measures, like, broadcast and unicast service ratio, service loss, waiting time and reneging probability. Based on the analytical expressions for these performance measures the existence of a single, optimal broadcast scheduling scheme is proved. The solution provides optimal performance with respect to system's throughput, grade and quality of service. This method is extended to design a hybrid unicast/broadcast scheduling scheme with user's retrials.

2.5 Summary

Broadly all scheduling can be divided into push and pull scheduling schemes. However, both push and pull scheduling schemes have their own limitations. Hence, a suitable combination of push and pull schemes is required to develop a hybrid scheduling strategy, which has the capability of improving the overall performance. In this chapter we have given a broad overview of the major existing push, pull and hybrid scheduling strategies. While most of the strategies attempt to minimize the client's waiting time, some are also focused on delay jitter, overall cost, consistency.

Table 2.1: Different Scheduling Strategies

No.	Work	Type	Performance Metric	Adaptability	Spl. Features
1	[1]	push	response time	no	<i>LIX, PIX</i> page replacement
2	[3]	pull	stretch value	no	<i>MAX, AMAX</i> BASE and EDF strategy
3	[4, 5]	pull	waiting time	no	scalable , <i>RxW</i> , combination of MRF and FCFS
4	[6]	pull	waiting time	no	LH-LRU replacement opportunistic schedule
5	[30]	hybrid	response time	yes	inaccurate data access info.
6	[9]	push	cost (poly. of access time)	no	asymptotic lower bound
7	[11]	push	jitter–period tradeoff	no	flexibility jitter-period
8	[14]	hybrid	delay	no	real toolkit, scalable, LRU cache, information-broker
9	[35]	hybrid	avrg. access time	yes	–
10	[31]	hybrid	access time messaging overhead	no no	lazy data request
11	[44]	hybrid	throughput abort	no no	data consistency concurrency
12	[8]	push	access time	no	separating service provider entity
13	[33]	push	expected delay	yes	sensitivity with items, disks and frequencies
14	[29]	push	access time query frequency	no	multiple data items
15	[21]	push	delay	yes	hierarchical data deliver model
16	[22]	push	message traffic	yes	group info loan-based slot-allocation feedback control
17	[26]	push	cost	no	$O(n \log k)$ competitive
18	[46]	pull	access time tuning time failure recovery	yes	largest delay cost first (LDFC)
19	[34]	hybrid	avrg. access time	yes	–
20	[7]	push	waiting time	no	file dependency
21	[32]	hybrid	average access time average completion time	yes	dynamic popularity of data items
22	[25]	push	broadcast cost	no approx. algos.	fast, polynomial approach
23	[19, 49]	push	access time	no	packet fair scheduling
24	[46]	push-pull	access time response time	yes	identical push- pull systems
25	[16]	push	requests scheduled missed deadlines	yes	time constraints
26	[27, 28]	push-pull	access time on-demand channels	yes	cost estimation of dynamic scheduling
27	[2]	hybrid	response time	no	scalability issues

Chapter 3

Hybrid Push-Pull Scheduling

In this chapter we introduce a new hybrid push-pull scheduling strategy. In short, the strategy partitions the entire set of items into push and pull sub-sets. It then strictly alternates between a push and a pull operation to transmit all the data items. While initially the system is operated on unit-length, homogeneous data items, the work is extended to include the heterogeneous, variable-length items also. The selection criteria for a push-item is based on *packet-fair scheduling* and a pull-item is selected on the basis of most request first (MRF) (for homogeneous items) and stretch-optimal scheduling (for heterogeneous items). The scheme is further enhanced to incorporate the role of client priorities to resolve the tie. Suitable performance modeling is done to analyze the average system performance. Simulation experiments support this performance analysis and points out the efficiency of the hybrid system in reducing the overall average access time.

3.1 Hybrid Scheduling for Unit-length Items

Before introducing our proposed hybrid scheduling for unit-length data items, we first highlight the assumptions we have used in our hybrid scheduling system.

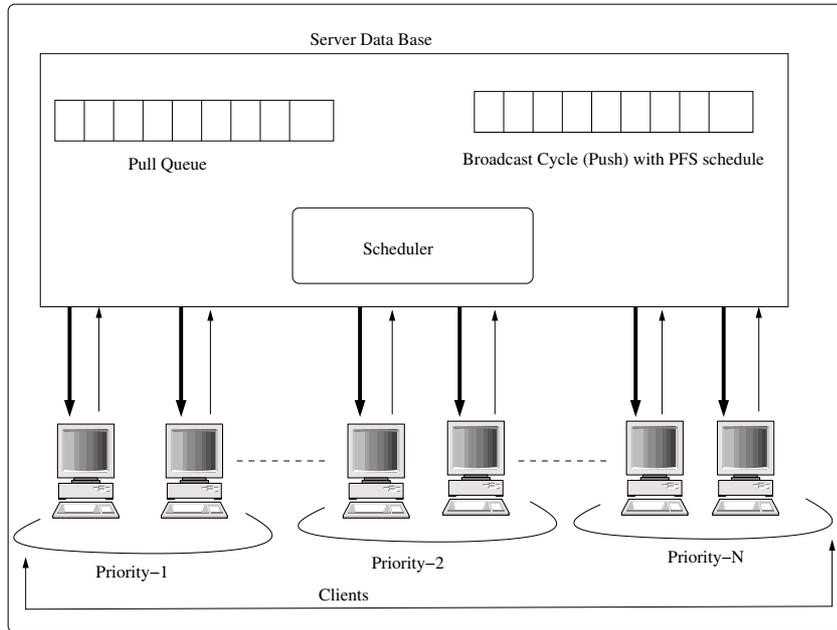


Figure 3.1: Asymmetric Hybrid Scheduling System

3.1.1 Assumptions and Motivations

1. We assume a system with a single server and multiple clients thereby imposing an asymmetry. Figure 3.1 shows the schematic diagram of such an asymmetric environment consisting of a single server and multiple clients with different priorities. The uplink bandwidth is much less than the down-link bandwidth.
2. The database at the server is assumed to be composed of D total number of distinct data items, each of unit length.
3. The *access probability* P_i of item i is a measure of its degree of popularity. We assume that the access probabilities P_i follow the Zipf's distribution with access *skew-coefficient* θ : $P_i = \frac{(1/i)^\theta}{\sum_{j=1}^n (1/j)^\theta}$. It is assumed that the server knows the access probability of each item in advance. The items are numbered from 1 to D in decreasing order of their ac-

cess probability, thus $P_1 \geq P_2 \geq \dots \geq P_D$. Clearly, from time to time, the server recomputes the access probability of the items, renumber them as necessary and eventually make available to all clients the new numbering of the items. It is assumed that one unit of time is the time required to **spread** an item of unit length.

We say that the client accesses an item if that item is *pushed*, while that item is *requested* if the item is *pulled*. Moreover, let the *load* N of the system be the number of requests/access arriving in the system for unit of time. Let the *access time*, $T_{acc,I}$ be the amount of time that a client waits for a data item i to be broadcast after it begins to listen. Moreover, let the *response time*, $T_{res,I}$ be the amount of time between the request of item i by the client and the data transmission. Clearly, the aim of the *push scheduling* is to keep the access time for each push item i as small as possible, while that of the *pull scheduling* is to minimize the response time for each pull item i . In a push-based system, one of the overall measures of the scheduling performance is called *average expected access time*, $T_{exp-acc}$, which is defined as $T_{exp-acc} = \sum_{i=1}^D P_i \cdot \overline{T_{acc,i}}$, where $\overline{T_{acc,i}}$ is the average expected access time for item i . If instances are equally spaced in the broadcast cycle, then $\overline{T_{acc,i}} = \frac{s_i}{2}$, where s_i is the spacing between the two instances of same item i . The push-scheduling is based on the packet fair scheduling algorithm. Similarly, it can be defined the *average expected response time*, denoted $T_{exp-res}$ for the pull scheduling.

In order to explain the rational behind our approach, let us first describe in details the intuition behind the hybrid scheduling in [18] and point out some of its drawbacks. To make the average expected access time of the system smaller, the solution in [18] flushes the pull queue. Let the *push-set* consist of the data items numbered from 1 up to K , termed from now on the *cut-off point*, and let the remaining items from $K + 1$ up to D form the *pull set*. Hence, the average expected waiting time for the hybrid

scheduling is defined as:

$$T_{exp-hyb} = T_{exp-acc} + T_{exp-res} = \sum_{i=1}^K P_i \cdot \overline{T_{acc,i}} + \sum_{i=K+1}^D P_i \cdot \overline{T_{res,i}}.$$

As the push-set becomes smaller, the average expected access time $T_{exp-acc}$ becomes shorter. However, the pull-set size becomes larger, leading to a longer expected response time $T_{exp-res}$. The size of the pull-set might also increase the average access time $\overline{T_{acc,i}}$, for every push item. In fact, if the hybrid scheduling serves, between any two items of the cyclic push scheduling, all the pending requests for pull items in First-Come-First-Served order, it holds for the average expected access time for item i : $\overline{T_{acc,i}} = (s_i + s_i \cdot q)/2$, where q is the average number of distinct pull items for which, arrives, at least one pending request in the pull-queue for unit of time. From now on, we refer to q as the *dilation* factor of the push scheduling. To limit the growth of the $\overline{T_{acc,i}}$, and therefore that of the $\overline{T_{exp-acc}}$, the push-set is taken in [18] enough large that, in average, no more than 1 request for all the pull items arrives during a single unit time. To guarantee a dilation factor q equal to 1 when the system load is equal to N , [18] introduces the concept of the *build-up point* B . B is the minimum index between 1 and D for which it holds $N(1 - \sum_{i=1}^B P_i) \leq 1$, where N is the average access/requests arriving at unit of time. In other words, [18] pushes all the items from 1 up to B to guarantee that no more than 1 item is waiting in the pull queue to be disseminate, and therefore to achieve $q = 1$. After having bounded the dilation factor to 1, [18] chooses as the cut-off point between the push and pull items the value K , with $K \geq B$, such that K minimizes the *average* expected waiting time for the hybrid system. Intuitively, the partition between push and pull items found out in [18] is meaningful only when the system load N is small and the access probabilities are much skewed. Under these conditions, indeed, the build-up point B is low. Hence, there may be a cut-off K ,

such that $B \leq K \leq D$, which improves on the average expected access time of the pure-push system. However, when either the system has a high load N and/or all items have almost the same degree of probability, the distinction between the high and low demand items becomes vague, artificial, hence the value of build-up point B increases, finally leading to the maximum number D of items in the system. Thus, in those cases, the solution proposed in [18] almost always behaves as a pure push-based system. To corroborate what discussed so far, in Table 3.1, the relation of the value of the load N of the distribution of the access skew coefficient θ with the value of the build up point B is illustrated, when the total number of distinct items D is 20.

3.1.2 The Basic Hybrid Push-Pull algorithm

We now present a hybrid scheduling that improves on [18] when the load is high or when the access probabilities are balanced, that is, when the scheduling in [18] reduces to the pure-push scheduling. The solution proposed in this paper again partitions the data items in the push-set and the pull-set, but it chooses the value of the cut-off point K between those two

θ	N	2	4	6	8	10	12	14	16	18	20
0.5		8	14	16	17	18	19	19	19	20	20
0.6		7	13	16	17	18	18	19	19	19	20
0.7		6	12	15	16	17	18	18	19	19	19
0.8		6	11	14	16	17	17	18	18	19	19
0.9		5	10	13	15	16	17	17	18	18	19
1.0		4	9	12	14	15	16	17	17	18	18
1.1		4	8	11	13	14	15	16	17	17	18
1.2		3	7	10	12	13	14	15	16	16	17
1.3		3	7	9	11	12	13	14	15	16	16

Table 3.1: Build-up point B for several values of N and θ when $D = 20$.

sets independent of the build-up point. Indeed, we let the pull-queue grow in size, and the push-set can contain any number of data items. After each single broadcast, we do not flush out the pull-queue, which may contain several different pending requests. In contrast, we just pull one single item: the item, which has the largest number of pending requests. Observe that simultaneously with every push and pull, N more access / requests arrive to the server, thus the pull-queue grows up drastically at the beginning. In particular, if the pull-set consists of the items from $K + 1$ up to D , at most $N * \sum_{j=K+1}^D P_j$ requests can be inserted in the pull-queue at every instance of time, out of which, only one, the pull item that has accumulated the largest number of requests, is extracted from the queue to be pulled. We are sure, however, that the number of distinct items in pull-queue cannot grow uncontrolled since the pull-queue can store at most as many distinct items as those in the pull-set, that is no more than $D - K$ items. So, after a while, the new arriving requests will only increase the number of clients waiting in the queue for some item, leaving unchanged the queue length. From this moment, we say that the system has reached a *steady state*. In other words, the pending requests will start to accumulate behind each pull-item without increasing anymore the queue length. Hence, just pulling the high demanded pull item, the system will not serve just one client but many. Our intuition is that a pull item cannot be stuck in the pull-queue for more than as many unit of time as the length of the queue. The push system, on the other hand, incurs an average delay of $\sum_{i=1}^K s_i P_i$, where $s_i = \frac{\sum_{j=1}^k \sqrt{\hat{P}_j}}{\sqrt{\hat{P}_i}}$, and $\hat{P}_i = \frac{P_i}{\sum_{j=1}^K P_j}$.

The server performs several actions simultaneously. From one side, it monitors the access probabilities of the data items and the system load. When those parameters diverge significantly from the assumptions previously made by the system, the server renumber the data items, and recalculates the cut-off point K to separate the push-set from the pull-set, as

```

Integer function CUT-OFF POINT ( $D, P = P_1, P_2 \dots P_D$ ) :  $K$ 
/*  $D$ : Total No. Of items in the Database of the server
 $P$ : Sorted vector of access probability of items in decreasing order
 $K$ : Optimal Cut off Point */
 $K := 1; T_{exp-hyb}(0) := T_{exp-hyb}(1) := D;$ 
while  $K \leq D$  and  $T_{exp-hyb}(K - 1) \geq T_{exp-hyb}(K)$  do
begin
Set  $s_i = \frac{\sum_{j=1}^k \sqrt{\hat{P}_j}}{\sqrt{\hat{P}_i}}$ , where  $\hat{P}_i = \frac{P_i}{\sum_{j=1}^K P_j}$ ,
 $T_{exp-hyb}(K) = \sum_{i=1}^K S_i P_i + \sum_{i=K+1}^D P_i * (D - K); K := K + 1;$ 
end
return ( $K - 1$ )

```

Figure 3.2: Algorithm to set the optimal cut-off point K

illustrated in Figure 3.2. Note that K is selected in such a way that the average expected waiting time of the hybrid scheduling $T_{exp-hyb}$ is minimized. In addition, the server listens to all the requests of the clients and manages the pull-queue. The pull-queue, implemented by a max-heap, keeps in its root, at any instant, the item with the highest number of pending requests. For any request i , if i is larger than the current cut-off point K , $i \geq K$, i is inserted in the pull-queue, the number of the pending requests for i is increased by one, and the heap information updates accordingly. On the other hand, if i is smaller than or equal to K , $i \leq K$, the server simply drops the request because that item will be broadcast by the push-scheduling. Finally, the server is in charge of deciding at each instant of time which item must be **spread**. The scheduling is derived as explained in Figure 3.3, where the details for obtaining the push scheduling (PFS) are omitted. Interested readers can find it in [19].

To retrieve a data item, a client performs the following actions (Figure 8.3):

```

Procedure HYBRID SCHEDULING;
while true do
begin
compute an item from the push scheduling and broadcast it;
if the pull-queue is not empty then
extract the most requested item from the pull-queue,
clear the number of pending requests for that item, and pull-it
end;

```

Figure 3.3: Algorithm at the Server End

3.2 Simulation Experiments

First of all, we compare the simulation results of the new algorithm with those of the hybrid scheduling in [18], with the results of the pure-push scheduling and with the analytic expression used to derive the optimal cut-off point. We run experiments for $D = 100$, for the total number of access / requests in the system $M = 25000$ and for $N = 10$ or $N = 20$. The results are reported in Table 2 and 3, respectively for $N = 10$ and $N = 20$. For both Tables 2 and 3, the value of θ is varied from 0.50 to 1.30, so as to have the access probabilities of the items initially from similar to very skewed. Note that for θ no larger than 1, the analytic average expected access time is close to that measured with the experiments. This confirms that, when the access probabilities are similar, the pull items remain in the pull-queue for a time no larger than to total number of pull items that is $D - K$. For larger values of θ , the experimental measure of the expected

```

Procedure CLIENT-REQUEST (i):
/* i : the item the client is interested in */
begin
send to the server the request for item i;
wait until listen for i on the channel
end

```

Figure 3.4: Algorithm at the Client Site.

	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30
New	40.30	37.78	35.23	32.36	29.38	25.95	22.95	19.90	17.04
[17]	44.54	42.35	40.01	37.31	34.12	29.93	24.38	20.61	17.04
Push	45.03	43.01	40.50	37.47	34.30	30.90	27.75	24.50	20.86
Analytical	36.01	36.21	35.04	33.56	29.94	29.73	27.09	25.19	22.51

Table 2: Expected hybrid access time for different values of θ (taken in the columns) and different algorithms (taken in the rows) when $N = 10$.

	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30
New	41.96	39.39	36.59	33.49	30.39	27.20	23.88	21.14	18.26
[17]	44.44	42.45	40.10	37.39	33.78	30.69	27.54	23.23	19.49
Push	44.70	42.61	40.30	37.65	34.12	30.78	27.71	23.94	21.07
Analytical	37.59	35.68	34.53	33.06	29.94	29.73	27.09	24.43	24.24

Table 3: Expected hybrid access time for different values of θ (taken in the columns) and different algorithms (taken in the rows) when $N = 20$.

response time is smaller than the analytic expected value because due to the fact that the access probabilities are very skew fewer than $D - K$ items can be present simultaneously in the pull-queue. Therefore, the actual waiting time of the client is eventually shorter than $D - K$. Further experimental results have shown that when θ is varied from 0.90 to 1.30; the length of the pull-queue is approximated better by the value $D * \sum_{i=K+1}^D P_i$ than by $D - K$. Moreover, as earlier discussed, when the system is highly loaded, the scheduling algorithm in [18], whose cut-off point K must be larger than the build-up point B , almost reduces to the pure-push scheduling. Contradictory to [18], the new hybrid algorithm, even with very high loaded system, experiments better results than a pure-push based system as illustrated in Figure 3.5 (A). Besides, in Figure 3.5 (B), the values of the cut-off point K for our solution, which takes K independent of B , and for the hybrid scheduling proposed in [18] are depicted for $N = 10$ and $N = 20$.

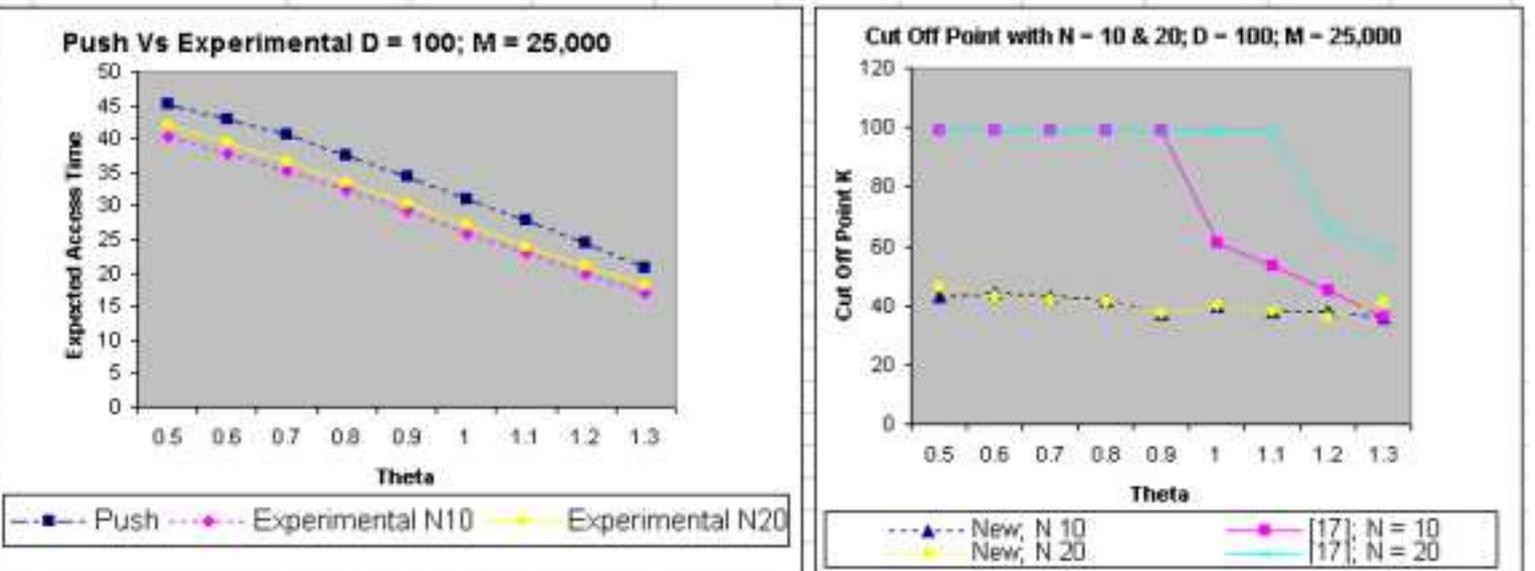


Fig. 4(A)

Fig. 4(B)

Figure 3.5: (A) Pure-Push scheduling Vs new algorithm; (B) Cut-Off Point when $N = 10, 20$.

3.3 Dynamic Hybrid Scheduling with Heterogeneous Items

The above-mentioned hybrid scheduling algorithm is extended to incorporate the heterogeneous data items and to resolve tie during selecting a pull-item [35, 41]. This variation of the lengths of the items result in difference in service time. Hence, the pull scheduling now needs to consider the item-length along with the number of request accumulated. This motivates us to use *stretch-optimal* scheduling principle.

3.3.1 Heterogeneous Hybrid Scheduling Algorithm

We still assume an ideal environment with a single server serving multiple clients, thereby imposing asymmetry. As earlier, the database at the server consists of a total number of D distinct items, out of which, K items are

pushed and the remaining $(D - K)$ items are pulled. However, the items now have variable lengths, and each item i has a different access probability P_i . The service time for an item is dependent on the size of that item. The larger the length of an item, the higher is its service time.

We have adopted PFS in our hybrid algorithm as the push mechanism. As before, the term push-scheduling will refer to the cyclic scheduling produced by the PFS algorithm applied to the push set. On the other hand, for the pull mechanism, we select the item that has maximum stretch-value $\mathcal{S}_i = \frac{\text{Request Count for item } i}{\text{Length}_i^2}$. We have assumed an ideal environment, where the client needs to send the server its request for the required item i along with its unique ID and waits until it listens for i on the channel (see Figure 3.6). Note that the behavior of the client is independent of the fact that the requested item belongs to the push-set or the pull-set. As mentioned earlier in Section 1.1, the Huges Network Network Systems DirecPC architecture [23] is a suitable example for such broadcast system.

```

Procedure CLIENT-REQUEST:
begin
    send to the server the request for a particular item
    with a unique id associated with the item;
    wait until listen for that item on the channel;
end

```

Figure 3.6: Client side algorithm

The server maintains the database of all items. The system starts as a pure pull-based scheduler (i.e., the push set is empty) assuming that all the items have the same access probability and few requests occur. Then, based on the requests received for each item during a certain interval of time, it dynamically moves to a hybrid system with the data items separated into the push set and the pull set. Precisely, at regular interval

```

Procedure Hybrid Scheduling;
while (true) do
begin
    Push-Phase:
        broadcast an item selected according to the Packet Fair Scheduling;
        handle the requests occurring during the push-phase;
    if the pull-queue is not empty then
    Pull-Phase:
        extract from the pull-queue the item whose stretch is maximum;
    if tie
        extract the item whose sum of the clients' priority is high;
    if tie
        extract the item with the smallest index;
        clear the number of pending requests for this item, and pull-it;
    handle the requests occurring during the pull-phase;
end;

```

Figure 3.7: Hybrid scheduling algorithm

of time, the server monitors the data access probabilities of the items and the arrival rate of the requests. If the values registered by the server significantly deviate by the values for which the current segregation point between the push and the pull sets has been computed, the cut-off point must be recomputed.

Once the cut-off point is fixed, the server continuously alternates a push-phase, in which a single item is broadcasted, and a pull-phase, in which a single item is disseminated, when there are clients waiting for pull items. After every push and every pull operation, the server accepts the set of requests arriving into the system. More precisely, the server simply collects statistics about the requests for the push items. After every push, if the pull queue is not empty, the server chooses the item whose stretch value is maximum. It might happen that more than one item have same stretch value. In that case, the server considers the item that has maxi-

imum priority. Priorities of the items are estimated by adding the priorities of the clients requesting that particular item, and then normalizing it. The ID of the client is used by the server to calculate its priority. Figure 3.7 provides the pseudo-code of the hybrid scheduling algorithm executing at the server-side while the push and pull sets do not change.

3.3.2 Modeling the System

In this section we evaluate the performance of our hybrid scheduling by developing suitable analytical models. The goal of this analysis is two-fold: it is used (i) to estimate the minimum expected waiting time (delay) of the hybrid system when the size of the push set is known, and (ii) to determine the cut-off point (K) between the push-set and pull-set when the system conditions (arrival rate and access probabilities) change. Indeed, since the waiting time is dependent on the size K of the push set, we investigate, by the analytical model, into the delay dynamics for different values of K in order to derive the cut-off point, that is the value of K that minimizes the system delay.

Before proceeding further, let us enumerate the parameters and assumptions used in our model:

1. The database consists of $D = \{1, \dots, D\}$ distinct items, sorted by non increasing access probabilities $\{P_1 \geq \dots \geq P_D\}$. Basically, the access probability gives a measure of item's popularity among the clients. We have assumed that the access probabilities (P_i) follow the *Zipf's distribution* with *access skew-coefficient* θ , such that $P_i = \frac{(1/i)^\theta}{\sum_{j=1}^n (1/j)^\theta}$. Every item has different length randomly distributed between $1-L$, where L is the maximum length.
2. Let C , K and $\varrho_{(cl)}$, respectively, denote the maximum number of clients, the size of the push set and priority of client cl . The server

pushes K items and clients pull the remaining $(D - K)$ items. Thus, the total probability of items in push-set and pull-set are respectively given by $\sum_{i=1}^K P_i$ and $\sum_{i=K+1}^D P_i = (1 - \sum_{i=1}^K P_i)$.

3. The service times of both the push and pull systems are exponentially distributed with mean μ_1 and μ_2 , respectively.
4. The arrival rate in the entire system is assumed to obey the Poisson distribution with mean $\lambda_{arrival}$.

Table 3.2 lists the symbols with their meanings used in the context of our analysis. Now, we are in a position to analyze the system performance for achieving the minimal waiting time.

Table 3.2: Symbols Used for Performance Analysis

<i>Symbols</i>	Descriptions
D	Maximum number of items
C	Maximum number of clients
i	Index of data item
K	Size of the the push set
P_i	Access Probability of item i
L_i	Length of item i
λ	Pull Queue Arrival Rate
$\lambda_{arrival}$	System Arrival Rate
μ_1	Push Queue Service Rate
μ_2	Pull Queue Service Rate
S_i	Space between the two instances of data item i
$\varrho_{(cl)}$	Priority of client cl
ϱ_i	Priority of data item i
$E[W_{pull}]$	Expected Waiting Time of Pull System
$E[W_{pull}^q]$	Expected Waiting Time of Pull Queue
$E[\mathcal{L}_{pull}]$	Expected Number of items in the Pull system
$E[\mathcal{L}_{pull}^q]$	Expected Number of items in the Pull queue

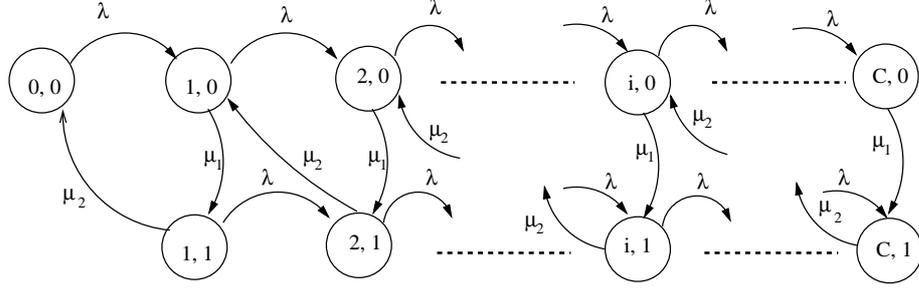


Figure 3.8: Performance Modeling of Our Hybrid System

Minimal Expected Waiting Time

Figure 3.8 illustrates the birth and death process of our system model, where the arrival rate in the pull-system is given by $\lambda = (1 - \sum_{i=1}^K P_i) \lambda_{arrival}$. First, we discuss the state space and possible transitions in this model.

1. Any state of the overall system is represented by the tuple (i, j) , where i represents the number of items in the pull-system and $j = 0$ (or 1) respectively represents whether the push-system (or pull-system) is being served.
2. The arrival of a data item in the pull-system results in the transition from state (i, j) to state $(i + 1, j)$, for $0 \leq i \leq C$ and $0 \leq j \leq 1$. However, the service of an item results in two different actions. Since the push system is governed by packet fair scheduling, the service of an item in the push-queue results in transition from state $(i, 0)$ to state $(i, 1)$, for $0 \leq i \leq C$. On the other hand, the service of an item in the pull queue results in transition from state $(i, 1)$ to the state $(i - 1, 0)$, for $1 \leq i \leq C$.
3. Naturally, the state $(0, 0)$ of the system represents that the pull-queue is empty and any subsequent service of the items in the push system leaves it in the same $(0, 0)$ state. Obviously, state $(0, 1)$ is not valid

because the service of an empty pull-queue is not possible.

In the steady-state, using the flow-balance conditions of *Chapman-Kolmogorov's* equation [17], we have the following equation for representing the initial system behavior:

$$p(0, 0) \lambda = p(1, 1) \mu_2 \quad (3.1)$$

where $p(i, j)$ represents the probability of state (i, j) . The overall behavior of the system for push (upper chain in Figure 3.8) and the pull system (lower chain in Figure 3.8) are given by the following two generalized equations:

$$p(i, 0)(\lambda + \mu_1) = p(i - 1, 0)\lambda + p(i + 1, 1)\mu_2 \quad (3.2)$$

$$p(i, 1)(\lambda + \mu_2) = p(i, 0)\mu_1 + p(i - 1, 1)\lambda \quad (3.3)$$

The most efficient way to solve of Equations (3.2) and (3.3) is using the *z-transforms* [17]. The resulting solutions are of the form:

$$P_1(z) = \sum_{i=0}^C p(i, 0) z^i \quad (3.4)$$

$$P_2(z) = \sum_{i=0}^C p(i, 1) z^i. \quad (3.5)$$

Now, dividing both sides of Equation (3.2) by μ_2 , letting $\rho = \frac{\lambda}{\mu_2}$ and $f = \frac{\mu_1}{\mu_2}$, performing subsequent *z*-transform as in Equation (3.4) and using Equation (3.1), we obtain

$$\begin{aligned} P_2(z) &= p(1, 1) + z(\rho + f)[P_1(z) - p(0, 0)] - \rho z^2 P_1(z) \\ &= \rho p(0, 0) + z(\rho + f)[P_1(z) - p(0, 0)] - \rho z^2 P_1(z) \end{aligned} \quad (3.6)$$

Similarly, transforming Equation (3.3) and performing subsequent derivations we get,

$$P_2(z) = \frac{f [P_1(z) - p(0, 0)]}{(1 + \rho - \rho z)} \quad (3.7)$$

Now, estimating the system behavior at the initial condition, we state the following normalization criteria:

1. The occupancy of pull states is the total traffic of pull queue and given by: $P_2(1) = \sum_{i=1}^C p(i, 1) = \rho$.
2. The occupancy of the push states (upper chain) is similarly given by: $P_1(1) = \sum_{i=1}^C p(i, 0) = (1 - \rho)$.

Using these two relations in Equation (3.6), the idle probability, $p(0, 0)$, is obtained as follows:

$$\begin{aligned}
P_2(1) &= \rho p(0, 0) + (\rho + f) [P_1(1) - p(0, 0)] - \rho P_1(1) & (3.8) \\
\rho &= \rho p(0, 0) + (\rho + f) [1 - \rho - p(0, 0)] - \rho (1 - \rho) \\
&= f(1 - \rho) - f p(0, 0) \\
f p(0, 0) &= f(1 - \rho) - \rho \\
p(0, 0) &= 1 - \rho - \frac{\rho}{f} \\
&= 1 - 2\rho, \text{ (if } \mu_1 = \mu_2)
\end{aligned}$$

Generalized solutions of Equations (3.6) and (3.7) to obtain all values of probabilities $p(i, j)$ become very complicated. Thus, the best possible way is to go for an expected measure of system performance, such as the average number of elements in the system and average waiting time. The most convenient way to derive the expected system performance is to differentiate the z -transformed variables, $P_1(z)$ and $P_2(z)$ and capture their values at $z = 1$. Thus, differentiating both sides of Equation (3.6) with respect to z at $z = 1$, we estimate the expected number of items in the pull-system, $E[\mathcal{L}_{pull}]$, as follows:

$$\begin{aligned}
\left[\frac{dP_2(z)}{dz} \right]_{z=1} &= (\rho + f) \left[\frac{dP_1(z)}{dz} \right]_{z=1} + P_1(1) (f - \rho) \\
&\quad - p(0, 0) (\rho + f) - \rho \left[\frac{dP_1(z)}{dz} \right]_{z=1} \\
E[\mathcal{L}_{pull}] &= (\rho + f) \mathcal{N} + (1 - \rho) - (\rho + f) \left(1 - \rho - \frac{\rho}{f} \right) - \rho \mathcal{N}
\end{aligned}$$

$$\begin{aligned}
&= \left(\frac{\mu_1}{\mu_2}\right) \mathcal{N} + \left(1 - \frac{\lambda}{\mu_2}\right) - \left(\frac{\lambda + \mu_1}{\mu_2}\right) \left(1 - \frac{\lambda}{\mu_2} - \frac{\lambda}{\mu_2}\right) \\
&= \mathcal{N} + \left(1 - \frac{\lambda}{\mu}\right) - \left(1 + \frac{\lambda}{\mu}\right) \left(1 - 2\frac{\lambda}{\mu}\right), \text{ (if } \mu_1 = \mu_2 = \mu)
\end{aligned} \tag{3.9}$$

where \mathcal{N} is the average number of users waiting in the pull queue when push is being served. Once we have the expected number of items in the pull system from Equation (3.9), using Little's formula [17] we can easily estimate the average waiting time of the system, $E[W_{pull}]$, average waiting time of the pull queue, $E[W_{pull}^q]$, and expected number of items, $E[\mathcal{L}_{pull}^q]$, in the pull queue as follows:

$$\begin{aligned}
E[W_{pull}] &= \frac{E[\mathcal{L}_{pull}]}{\lambda} \\
E[\mathcal{L}_{pull}^q] &= E[\mathcal{L}_{pull}] - \frac{\lambda}{\mu_2} \\
E[W_{pull}^q] &= E[W_{pull}] - \frac{1}{\mu_2}
\end{aligned} \tag{3.10}$$

Note that, there is a subtle difference between the concept of pull system and pull queue. While the pull queue considers only the items waiting for service in the queue, the pull system also includes the item(s) currently being serviced. However, the expected waiting time for the pull system discussed above does not consider the priorities associated with the individual data items. Such estimate can suffice the need for average system performance when every item in the pull queue has accumulated different number of requests. However, when any two items contain the same number of pending requests, the priorities associated with those two items come into consideration. This will affect the arrival and service of the individual data items. Thus, a smart system should consider the priorities of the data items influenced by the client priorities.

Role of Client Priorities:

Any client j is associated with a certain priority $\varrho(j)$ that reveals its importance. The priority of a particular data item is derived from the total normalized priorities of all the clients currently requesting for that data item. Thus, if a particular data item i is requested by a set \mathcal{C} of clients, then its priority is estimated as: $\varrho_i = \frac{1}{|\mathcal{C}|} \times \sum_{j \in \mathcal{C}} \varrho(j)$. The lower the value of $\varrho_{(cl)}$, the higher is the priority. When two items have the same stretch value, the item with higher priority is serviced first. This is also practical since such an item is requested by more important clients than its counterpart. Considering a non-preemptive system with many priorities, let us assume the data items with priority ϱ_i have an arrival rate λ_i and service time μ_{2_i} . The occupancy arising due to this j th data item is represented by $\rho_i = \frac{\lambda_i}{\mu_{2_i}}$, for $1 \leq i \leq max$, where max represents maximum possible value of priority. Also, let $\sigma_i = \sum_{x=1}^i \rho_x$. In the boundary conditions we have, $\sigma_0 = 0$ and $\sigma_{max} = \rho$. If we assume that a data item of priority x arrives at time t_0 and gets serviced at time t_1 , then the waiting time is $t_1 - t_0$.

Let at t_0 , there be n_i data items present having priorities i . Also let, S_0 be the time required to finish the data item already in service, and S_i be the total time required to serve n_i . During the waiting time of any data item, n'_i new items having the same number of pending requests and higher priority can arrive and go to service before the current item. If S'_i be the total time required to service all the n'_i items, then the expected waiting time will be,

$$E[W_{pull}^{q(x)}] = \sum_{i=1}^{x-1} E[S'_i] + \sum_{i=1}^x E[S_i] + E[S_0] \quad (3.11)$$

In order to get a reasonable estimate of $W_{pull}^{q(i)}$, three components of Equation (3.11) needs to be evaluated individually.

- (i) *Estimating $E[S_0]$* : The random variable S_0 actually represents the remaining service time, and achieves a value 0 for idle system. Thus,

the computation of $E[S_0]$ is performed in the following way:

$$\begin{aligned}
E[S_0] &= Pr[\text{Busy-System}] \times E[S_0|\text{Busy-System}] \\
&= \rho \sum_{i=1}^{max} E[S_0|\text{Serving items having priority-i}] \\
&\quad \times Pr[\text{items having priority i}] \\
&= \rho \sum_{i=1}^{max} \frac{\rho_i}{\rho \mu_{2_i}} \\
&= \sum_{i=1}^{max} \frac{\rho_i}{\mu_{2_i}} \tag{3.12}
\end{aligned}$$

(ii) *Estimating $E[S_i]$* : The inherent independence of Poisson process gives the flexibility to assume the service time $S_i^{(n)}$ of all n_i customers to be independent. Thus, $E[S_i]$ can be estimated using the following steps:

$$\begin{aligned}
E[S_i] &= E[n_i S_i^{(n)}] = E[n_i] E[S_i^{(n)}] \\
&= \frac{E[n_i]}{\mu_{2_i}} \rho_i E[W_{pull}^{q(i)}] \tag{3.13}
\end{aligned}$$

(iii) *Estimating $E[S'_i]$* : Proceeding in a similar way and assuming the uniform property of Poisson,

$$E[S'_i] = \frac{E[n'_i]}{\mu_{2_i}} \rho_j E[W_{pull}^{q(x)}] \tag{3.14}$$

The solution of Equation (3.11) can be achieved by combining the results of Equations (3.12)–(3.14) and using Cobham's iterative induction [17]. Finally, the new overall expected waiting time of the pull system ($E[\widehat{W}_{pull}^q]$) is achieved in the following manner:

$$E[W_{pull}^{q(x)}] = \frac{\sum_{i=1}^{max} \rho_i / \mu_{2_i}}{(1 - \sigma_{x-1})(1 - \sigma_x)} \tag{3.15}$$

$$E[\widehat{W}_{pull}^q] = \sum_{x=1}^{max} \frac{\lambda_x E[W_{pull}^{q(x)}]}{\lambda} \tag{3.16}$$

Thus, the expected access-time, $E[T_{hyb-acc}]$, of our hybrid system is given by:

$$E[T_{hyb-acc}] = E[\mathcal{L}_{pull}] \sum_{i=1}^K \frac{s_i}{2} P_i + E[\widehat{W}_{pull}^q] \times \sum_{i=K+1}^D P_i, \quad (3.17)$$

where according to the packet-fair-scheduling, $s_i = \left[\sum_{i=1}^M \sqrt{\hat{P}_i l_i} \right] \sqrt{\frac{l_i}{\hat{P}_i}}$ and $\hat{P}_i = \frac{P_i}{\sum_{j=1}^K P_j}$. The above expression provides an estimate of the average behavior of our hybrid scheduling system.

Estimation of the Cut-off value

One important system parameter which needs to be investigated is the cut-off point, that is the value of K which minimizes the expected waiting time in the hybrid system. It is quite clear from Equations (3.9)–(3.17) that the dynamics of minimum expected waiting time (delay) is governed by K . Furthermore, Equation (3.17) has two components for the minimum expected waiting time. While $\sum_{i=1}^K \frac{s_i}{2} P_i$ provides an estimate for the delay accumulated from the push system, $E[\widehat{W}_{pull}^q] \times \sum_{i=K+1}^D P_i$ represents the delay component arising from the pull system. For different values of K , these two components change dynamically. Intuitively, for low values of K , most of the items are pulled and the significant delay is accrued from the pulled items. The scenario gets reversed for high values of K . It seems hard to derive a closed form solution for the optimal value of K . The cut-off-point can be obtained algorithmically by estimating both the delay components and overall expected delay at each iteration and preserving the value of K which provides minimum expected delay. Alternatively to derive the cut-off point, for a fixed value D , we analyze the pattern of the expected waiting time with different values of K and fit the values to obtain a closed form equation of the pattern. We have used *polynomial fit* with degree 3 to identify these patterns for 3 different values of the access skew coefficient, $\theta = \{0.40, 0.80, 1.20\}$. This leads to the equations

for $E[T_{hybacc}] = f(K)$. For the sake of notational simplicity, we use y to represent $E[T_{hybacc}]$. We first differentiate y with respect to K to get the first derivative $\frac{\partial y}{\partial K}$. At the extreme points (maxima or minima) the derivative will be 0. Hence, the expression for $\frac{\partial y}{\partial K}$ is made equal to 0 to get the extreme values of K . As the polynomial is of degree 3, the slope of the curve $\frac{\partial y}{\partial K}$ is of degree 2. Hence, two possible values of K are possible. We have taken only that value of K which falls in the range $0 \leq K \leq D$, as the minimum and maximum possible values of cut-off point are 0 and D , respectively. At this particular value of K , we compute the value of y using the original equation. This is the minimum expected access time with corresponding cut-off-point for a particular value of θ . In order to check the minima, we have also computed the second order derivative with respect to K and showed this derivative is positive (minimality condition) for that K . This is repeated for $\theta = \{0.40, 0.80, 1.20\}$.

For example, the following three optimal values of K achieves the minimum waiting time for different values of θ and $D = 100$. When $\theta = 0.40$,

$$\begin{aligned}
y &= 27 \times 10^{-5}K^3 - 0.028K^2 - 0.5K + 160 \\
\left[\frac{\partial y}{\partial K} \right]_{min_y} &= 81 \times 10^{-5}K^2 - 0.056K - 0.5 = 0 \\
K &= 77 \\
y &= 78.75191
\end{aligned} \tag{3.18}$$

When $\theta = 0.80$

$$\begin{aligned}
y &= 13 \times 10^{-5}K^3 - 0.11K^2 - 0.34K + 100 \\
\left[\frac{\partial y}{\partial K} \right]_{min_y} &= 39 \times 10^{-5}K^2 - 0.22K - 0.34 = 0 \\
K &= 69 \\
y &= 66.875
\end{aligned} \tag{3.19}$$

When $\theta = 1.20$

$$\begin{aligned}
 y &= 0.01K^2 - 4 \times 10^{-5}K^3 - 0.62K + 55 \\
 \left[\frac{\partial y}{\partial K} \right]_{\min_y} &= 0.02K - 12 \times 10^{-5}K^2 - 0.62 = 0 \\
 K &= 41 \\
 y &= 43.633
 \end{aligned}
 \tag{3.20}$$

Figure 3.9 shows the variation of expected access time with different values of the size of the push set. The overall expected waiting time always achieves more or less a parabolic (bell-shaped) form with the global minima occurring at $K = \{77, 69, 41\}$ for $\theta = \{0.40, 0.80, 1.20\}$, respectively. The corresponding minimum expected waiting time is $\{79, 67, 44\}$ time units.

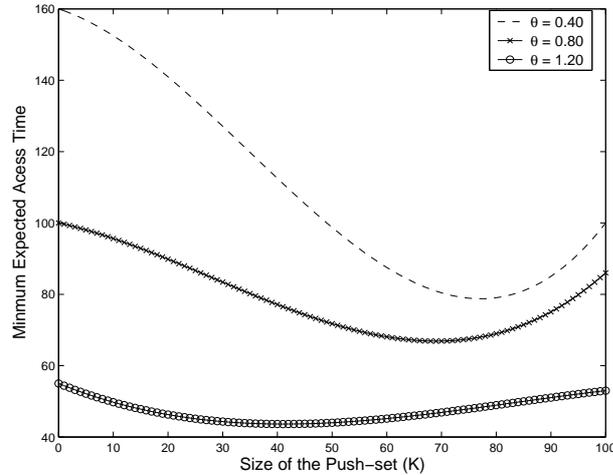


Figure 3.9: Variation of Expected Access Time with the Size of the Push Set

3.4 Experimental Results

In this section we validate our hybrid system by performing simulation experiments. The primary goal is to reduce the expected access time.

We enumerate below the salient assumptions and parameters used in our simulation.

1. Simulation experiments are evaluated for a total number of $D = 100$ data items.
2. Arrival rate, $\lambda_{arrival}$, is varied between 5–20. The values of μ_1 and μ_2 are estimated as: $\mu_1 = \sum_{i=1}^K (P_i \times L_i)$ and $\mu_2 = \sum_{i=K+1}^D (P_i \times L_i)$.
3. Length of data items is varied from 1 to 5. An average length of 2 is assumed.
4. Every client is assumed to have some priority randomly assigned between 1 and 5. These priorities are so defined that the lower the value, the higher the priority.
5. To keep the access probabilities of the items from being similar to very skewed, θ is dynamically varied from 0.20 to 1.40.
6. To compare the performance of our hybrid system, we have chosen 4 different hybrid scheduling strategies [31, 32, 18, 45] as performance benchmarks.

Figures 3.10 and 3.11 respectively demonstrate the variation of the expected access-time with different values of K and θ , for $\lambda = 10$ and $\lambda = 20$, in our hybrid scheduling algorithm. In both cases, the expected access-time is minimum (~ 40 time units) for high values of θ (~ 1.3) and moderate K . With decreasing values of K , the expected access-time increases. This is because as K decreases, the number of items in the pull queue increases and those items take much more time to get serviced. On the other hand, the average access time also increases for very high values of K . This is because for pretty high K , the push set becomes very large and the system

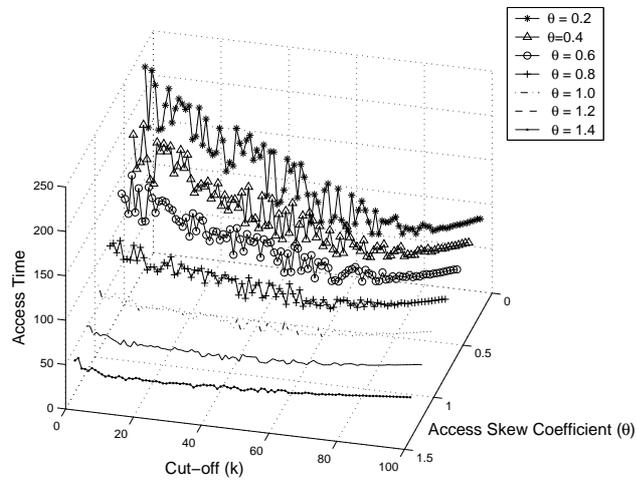


Figure 3.10: System Behavior with $\lambda = 10$

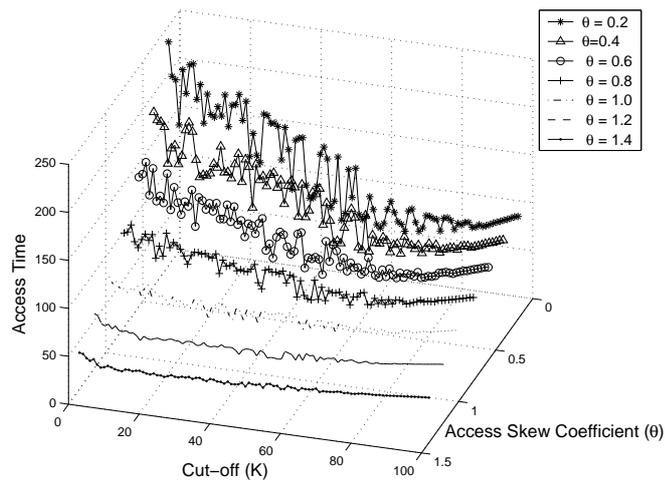


Figure 3.11: System Behavior with $\lambda = 20$

repeatedly broadcasts data items which are even not popular. Thus, the optimal performance is achieved when K is in the range 40–60.

Figure 3.12 shows the results of performance comparison, in terms of expected access time (in seconds), between our newly proposed hybrid algorithm with three existing hybrid schemes due to Su, et al. [45], Oh, et al. [32], and Guo, et. al. [18]. The plots reveal that our new algorithm

achieves an improvement of $\sim 2 - 6$ secs. The possible reasons lie in the fact that while these existing scheduling algorithms use MRF and Flat scheduling to select an item for transmission from the pull and push systems, our new algorithm uses the *stretch*, i.e., *max-request min-service-time* based scheduling and *packet fair scheduling* for pull and push systems, respectively. The effective combination of these two scheduling principles result in the lower expected access time in our hybrid scheduling algorithm.

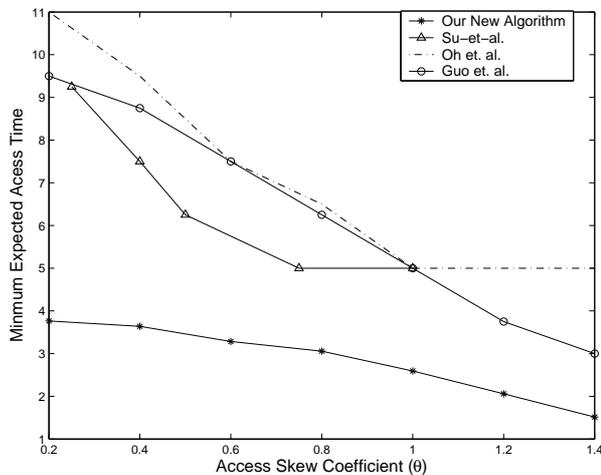


Figure 3.12: Performance comparison with varying skewness

In order to demonstrate the performance efficiency of the proposed hybrid scheduling, we have also looked into the *minimum expected access time* (for a particular K and θ) with different arrival rates (λ). The hybrid scheduling algorithm due to [31] is chosen for comparison. Figure 3.13 points out that our algorithm consistently gains over existing hybrid scheduling [31] with different arrival rates. Note that the variation of expected access time with different arrival rates is pretty low. This also demonstrates the stability of our hybrid scheduling system.

Figure 3.14 depicts the comparative view of the analytical results, provided in Equation (3.17), with the simulation results of our hybrid schedul-

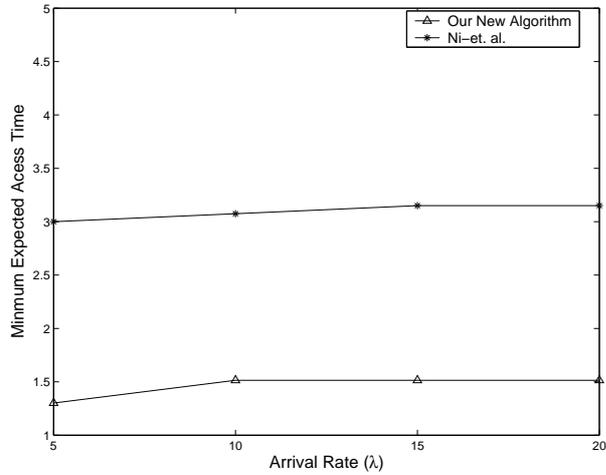


Figure 3.13: Performance comparison with different arrival

ing scheme. The analytical results closely match with the simulation results for expected access time with almost $\sim 90\%$ and $\sim 93\%$ accuracy for $\lambda = 5$ and $\lambda = 20$, respectively. Thus, we can conclude that the performance analysis is capable of capturing the average system behavior with good accuracy. The little ($\sim 7-10\%$) difference exists because of the assumption of memory-less property associated with arrival rates and service times in the system.

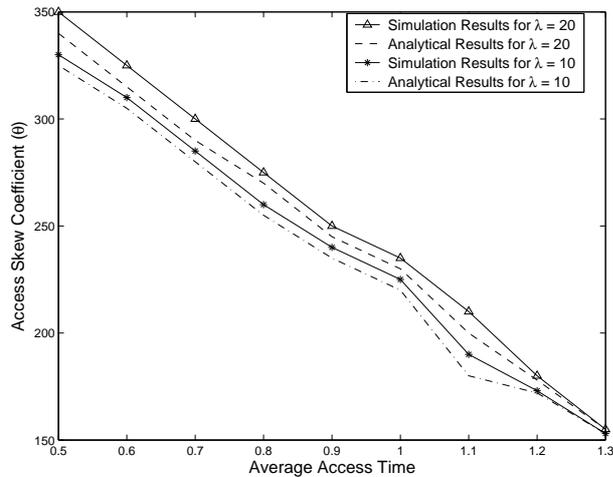


Figure 3.14: Simulation Vs Analytical Results

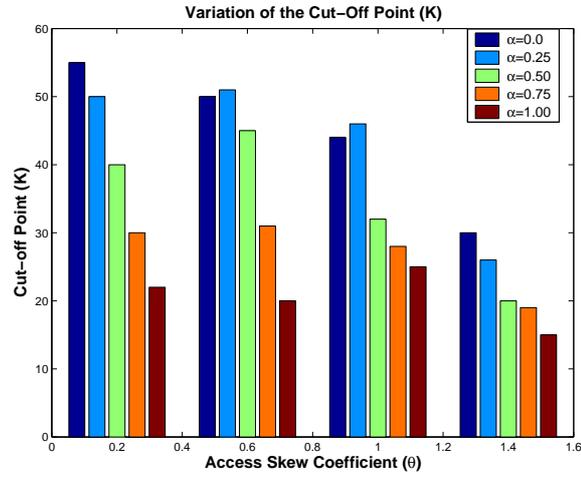


Figure 3.15: Variation of Cutoff-point (K)

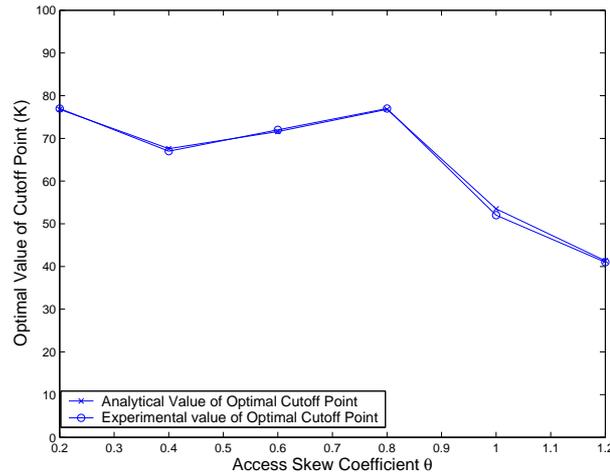


Figure 3.16: Simulation Vs Analytical Results of the Optimal Cut-Off point (K)

Let us now investigate the dynamics of the cut-off point (K) achieved by our hybrid scheduling strategy. Figure 3.15 demonstrates that K lies in the range of 40–60 for three different arrival rates such as $\lambda = [5, 10, 20]$. Intuitively, this points out that the system has achieved a fair balance between push and pull systems, thereby efficiently combining both the scheduling strategies to achieve the minimum expected access time.

Figure 3.16 provides the comparison of the variation of optimal cut-off point provided by simulation and analytical results, for different values of access skew coefficient, θ . The plots point out that the simulation and analytical results of optimal cut-off point closely matches with a difference of only $\sim 1\%$ - 2% .

3.5 Summary

In this chapter we have proposed a new framework for hybrid scheduling in asymmetric wireless environments. The framework is initially designed for homogeneous, unit-length items. The push system operates on PFS and the pull part is based on MRF scheduling. The cutoff point used to separate push and pull system is determined such that the overall expected access delay is minimized. Subsequently, the system is enhanced to include the items of heterogeneous lengths. In order to take the heterogeneity into account, the pull part is now based on stretch-optimal scheduling. Performance modeling, analysis and simulation results are performed to get an overall picture of the hybrid scheduling framework.

Chapter 4

Adaptive Push-Pull Algorithm with Performance Guarantee

A dynamic hybrid scheduling [37] is proposed, which does not combine the push and pull in a static, sequential order. Instead, it combines the push and pull strategies *probabilistically depending on the number of items present and their popularity*. In practical systems, the number of items in push and pull set can vary. For a system with more items in the push-set (pull-set) than the pull-set (push-set), it is more effective to perform multiple push (pull) operations before one pull (push) operation.

The cut-off point, that is the separation between the push and the pull items, is determined in such a way that the clients are served before the deadline specified at the time of the request. In other words, the major novelty of our system lies in its capability of offering a performance guarantee to the clients. Once that the analytic model has been devised, we take advantage from it to make our system more flexible. Indeed, since by the analytic model the system performance is already known with a good precision, it is possible to decide in advance if the value of K currently in use at the server will satisfy the client request on time. If not, K is updated in a suitable way again looking at the system performance analysis.

4.1 Adaptive Dynamic Hybrid Scheduling Algorithm

The strict sequential combination of push and pull fails to explore the system's current condition. In practical systems, it is a better idea to perform more than one push operations followed by multiple pull operations, depending on the number of items currently present in the system. The algorithm needs to be smart and efficient enough to get a good estimate of these number of continuous push and pull operations. Our proposed hybrid scheduling scheme performs this strategy based on the number of items present and their popularity.

We have assumed a single server, multiple clients and a database consisting of D distinct items, of which K items are pushed and the remaining $(D - K)$ items are pulled. The access probability P_i of an item i is governed by the Zipf's distribution and depends on the access skew-coefficient θ . When θ is small (value close to 0), P_i is well balanced but as θ increases (value close to 1), the popularity of the data items becomes skewed. From time to time the value of θ is changed dynamically for our hybrid system, which in turn, results in dynamic variation of P_i and the size of the push and pull sets. PFS and MRF techniques are used for selecting the item to be pushed and pulled respectively. After every push or pull operation, the next push or pull operation is probabilistically determined using the following equation:

$$\begin{aligned}
 \gamma_1 &= Pr[push|push] = \frac{K}{D} \sum_{i=1}^K P_i \\
 \gamma_2 &= Pr[pull|push] = 1 - \gamma_1 \\
 \gamma_3 &= Pr[pull|pull] = \frac{D-K}{D} \sum_{i=K+1}^D P_i \\
 \gamma_4 &= Pr[push|pull] = 1 - \gamma_3
 \end{aligned}
 \tag{4.1}$$

In other words, at the end of every push operation the system checks if γ_1 . If $\gamma_1 \geq Pr_1$ (where Pr_1 is a pre-defined value), the system goes for another push, else it switches to the pull-mode. Similarly, at the end of every pull operation, it computes the value of γ_3 . If $\gamma_3 \geq Pr_2$ (Pr_2 is pre-defined) then the system performs another pull operation, else it switches to the push mode.

```

Procedure HYBRID SCHEDULING ( $Pr_1, Pr_2$ );
while true do
  begin
    1. select an item using PFS and push it;
    2. consider new arrival requests;
    3. ignore the requests for push item;
    4. append the requests for items in the
       pull queue;
    5. compute probabilities of  $\gamma_1$  and  $\gamma_2$ 
    6. if ( $Pr_1 \leq \gamma_1$ ) goto step 1
    7. else goto step 8
    8. if pull-queue is not empty then
        9. use MRF to extract an item from pull
           queue;
        10. clear pending requests for that item;
        11. Pull that particular item;
        12. consider new arrival requests;
        13. ignore the requests for push item;
        14. append the requests for items in
            pull queue;
      end-if
    15. compute probabilities of  $\gamma_3$  and  $\gamma_4$ 
    16. if ( $Pr_2 \leq \gamma_3$ ) goto step 8
        else goto step 1;
  end-while

```

Figure 4.1: Hybrid Scheduling Algorithm at the Server

At the server end, the system starts as a pure pull-based scheduler. If the request is for a push item, the server simply ignores the request as the item will be pushed according to the PFS algorithm sooner. However

if the request is for a pull item, the server inserts it into the pull queue with the associated arrival time and updates its stretch value. Figure 4.1 provides the pseudo-code of the hybrid scheduling algorithm executing at the server-side.

4.1.1 Analytical Underpinnings

In this section we investigate into the performance evaluation of our hybrid scheduling system by developing suitable analytical models. The arrival rate in the entire system is assumed to obey the Poisson distribution with mean λ_1 . The service times of both the push and pull systems are exponentially distributed with mean μ_1 and μ_2 , respectively. The server pushes K items and clients pull the rest $(D - K)$ items. Thus, the total probability of items in push-set and pull-set are respectively given by $\sum_{i=1}^K P_i$ and $\sum_{i=K+1}^D P_i = (1 - \sum_{i=1}^K P_i)$, where P_i denotes the access probability of item i . We have assumed that the access probabilities P_i follow the *Zipf's distribution* with *access skew-coefficient* θ , such that, $P_i = \frac{(1/i)^\theta}{\sum_{j=1}^n (1/j)^\theta}$. After every push the server performs another push with probability γ_1 and a pull with probability γ_2 . Similarly, after every pull it performs another pull with probability γ_3 and a push with probability γ_4 .

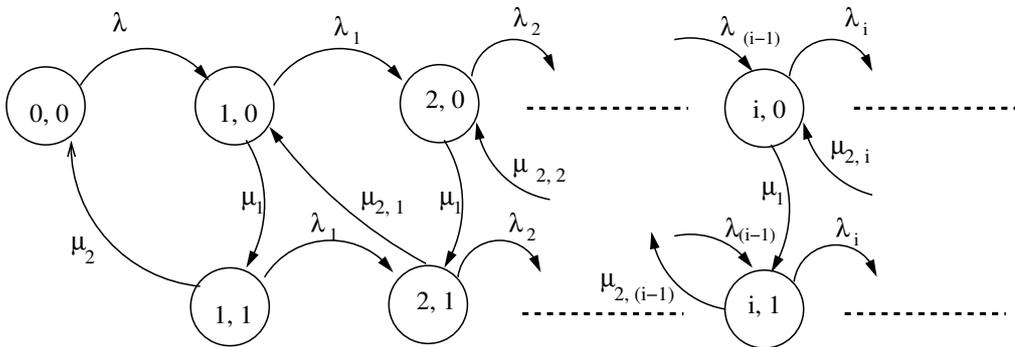


Figure 4.2: Performance Modelling of Hybrid System

Figure 4.2 illustrates the underlying birth and death process of our

system, where the arrival rate in the pull-system is given by $\lambda = (1 - \sum_{i=1}^K P_i)\lambda_1$. Any state of the overall system is represented by the tuple (i, j) , where i represents the number of items in the pull-system. On the other hand, j is a binary variable, with $j = 0$ (or 1) respectively representing whether the push-system (or pull-system) is currently being served by the server.

The arrival of a data item in the pull-system, results in the transition from state (i, j) to state $(i + 1, j)$, $\forall i$, such that $0 \leq i < \infty$ and $\forall j \in [0, 1]$. The service results in different actions. The service of an item in the push-queue results in transition of the system from state $(i, j = 0)$ to state $(i, j = 1)$, with probability γ_2 , $\forall i$ such that $0 \leq i < \infty$. With probability γ_1 the push-service makes the system to remain in same state. On the other hand, the service of an item in the pull results in transition of the system from state $(i, j = 1)$ to the state $(i - 1, j = 0)$, with probability γ_4 and state $(i - 1, j = 1)$ with probability γ_3 , $\forall i$, such that $1 \leq i < \infty$. The state of the system at $(i = 0, j = 0)$ represents that the pull-queue is empty and any subsequent service of the elements of push system leaves the system in the same $(0, 0)$ state. Obviously, the state $(i = 0, j = 1)$ is not valid because the service of an empty pull-queue is not possible.

In the steady-state, using the flow-balance conditions of *Chapman-Kolmogorov's* equation [17], we have the following three equations representing the system's behavior:

$$p(i, 0) = \frac{p(i - 1, 0)\lambda + p(i + 1, 1)\gamma_4\mu_2}{(\lambda + \gamma_2\mu_1)} \quad (4.2)$$

$$p(i, 1) = \frac{p(i, 0)\gamma_2\mu_1 + p(i - 1, 1)\lambda}{(\lambda + \gamma_3\mu_2 + \gamma_4\mu_2)} \quad (4.3)$$

$$p(0, 0) \lambda = p(1, 1) \mu_2, \quad (4.4)$$

where $p(i, j)$ represents the probability of state (i, j) . While the first two equations represents the overall behavior of the system for push (upper

chain) and the pull system (lower chain), the last equation actually represents the initial condition of the system. The most efficient way to solve the above Equations is using z -transforms [17]. Performing z -transforms of Equation 4.2 and Equation 4.3 and using the initial condition, we get a pair of transformed equations:

$$P_2(z)\gamma_4\mu_2 = z[P_1(z) - p(0,0)](\lambda + \gamma_2\mu_1) - z^2\lambda P_1(z) + p(1,1)\gamma_4\mu_2 \quad (4.5)$$

$$P_2(z) = \frac{\gamma_2\mu_1[P_1(z) - p(0,0)]}{(\lambda + \gamma_3\mu_2 + \gamma_4\mu_2 - z\lambda)} \quad (4.6)$$

Now, estimating the system behavior at the initial condition, we can state the following normalization criteria: The occupancy of pull states is the total traffic of pull queue and is given by: $P_2(1) = \sum_{i=1}^C p(i,1) = \rho$. The occupancy of the push states (upper chain) is similarly given by: $P_1(1) = \sum_{i=1}^C p(i,0) = (1 - \rho)$. Using these two relations in Equation (4.5), we can obtain the initial probability, $p(0,0)$. The initial probability of the system, i.e. probability of an empty pull queue is given by the following equation:

$$p(0,0) = \frac{\mu_1(\gamma_2 - \gamma_2\rho - \rho\gamma_4\mu_2)}{\lambda + \gamma_2\mu_1 - \gamma_4\lambda} \quad (4.7)$$

Generalized solutions of Equations (4.5) to obtain all values of probabilities $p(i,j)$ become very complicated. Thus, the best possible way is to go for an expected measure of system performance, such as the average number of elements in the system and average waiting time. The most convenient way to obtain this expected system performance is to differentiate the z -transformed equation (Equation (4.5)), and capture the values of the z -transformed variable at $z = 1$.

$$\gamma_4\mu_2 \frac{dP_2(z)}{dz} \Big|_{z=1} = \gamma_2\mu_1 \frac{dP_1(z)}{dz} \Big|_{z=1} + (1 - \rho)(\gamma_2\mu_1 - \lambda)$$

$$E[\mathcal{L}_{pull}^q] = \frac{p(0,0)(\lambda + \gamma_2\mu_1)}{\frac{dP_2(z)}{dz}\big|_{z=1}}, \quad (4.8)$$

where $\frac{dP_1(z)}{dz}\big|_{z=1}$ gives the number of elements in push system in PFS. Once, we have the expected number of items in the pull system from Equation (4.8), using Little's formula [17], we can easily obtain the estimates of average waiting time of the system ($E[W_{pull}]$), and expected number of items ($E[\mathcal{L}_{pull}^q]$) in the pull queue as:

$$E[W_{pull}^q] = E[W_{pull}] - \frac{1}{\mu_2} = \frac{E[\mathcal{L}_{pull}^q]}{\lambda} - \frac{1}{\mu_2} \quad (4.9)$$

If K represents the number of items in the push system, then the expected cycle-time of the push system is given by: $\sum_{i=1}^K \frac{S_i P_i}{(1-\rho)\mu_1}$. Hence, the expected access-time ($E[T_{hyb-acc}]$) of our hybrid system is given by:

$$E[T_{hyb-acc}] = \sum_{i=1}^K s_i P_i + E[W_{pull}^q] \times \sum_{i=k+1}^D P_i, \quad (4.10)$$

where according to the packet-fair-scheduling, $s_i = \frac{\sum_{j=1}^K \sqrt{\hat{P}_j}}{\sqrt{\hat{P}_i}}$ and $\hat{P}_i = \frac{P_i}{\sum_{j=1}^K P_j}$. The above expression provides an estimate of the average behavior of our hybrid system.

4.1.2 Simulation Experiments

In this section we perform the experiments to demonstrate the performance efficiency of our hybrid system. In order to compare the performance of our hybrid system, we have chosen our previous hybrid scheduling algorithm [34] as performance bench-marks. The prime goal of the entire scheme is to reduce the expected access time. Before going into the details of the simulation results, we enumerate the assumptions we have used in our simulation.

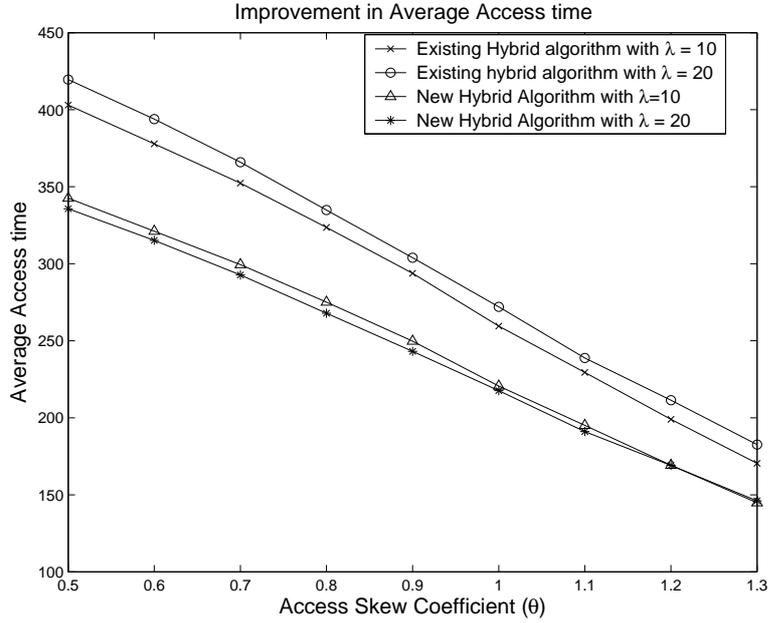


Figure 4.3: Improvement in Average Access Time

1. The simulation experiments are evaluated for $D = 1,000$ items. The system performs a push and pull operation in a reciprocal manner, unless the pull queue is empty.
2. In order to remain consistent with the analysis, the arrival and service rates are assumed to obey Poisson distribution. The average value of arrival rate (λ) is taken to be 10 and 20. The average value of service rates (push and pull), μ_1 and μ_2 are assumed to be 1.
3. In order to keep the access probabilities of the items from similar to very skewed, θ is dynamically varied from 0.50 to 1.50.

Figure 4.3 demonstrate the variation of expected access-time with different values of θ , for arrival-rates of 10 and 20 respectively, in our hybrid scheduling algorithm, for 1000 items. Note that, in both cases, the expected access-time for our new hybrid scheduling is sufficiently lower than the expected access time for existing hybrid scheduling. The prime rea-

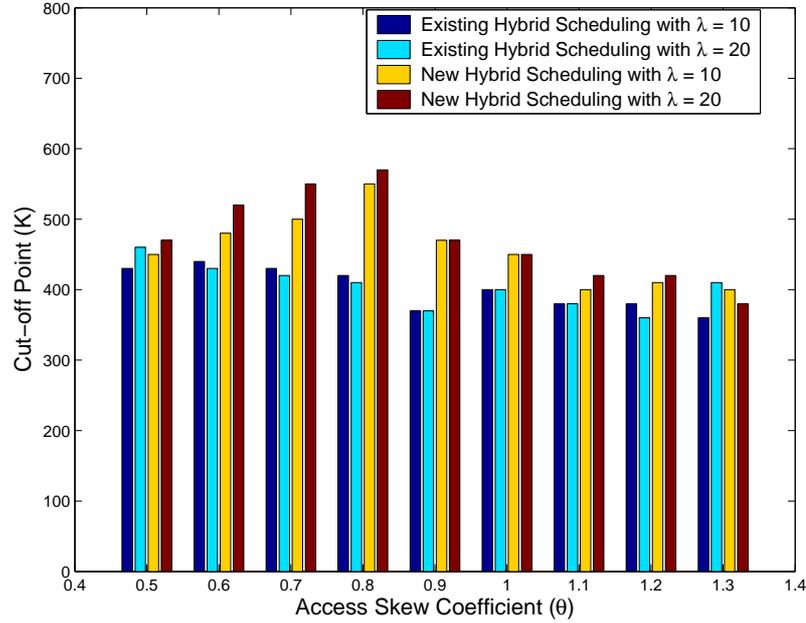


Figure 4.4: Dynamics of Cutoff Point

son behind this lies in the fact that the hybrid scheduling captures the requirement of the system by probabilistically combining push and pull-based scheduling principles. Figure 4.4 shows that the hybrid scheduling achieves a cut-off point in the range 360–430 and 360–460 respectively for arrival rates of 10 and 20 with 1000 data items. This explains the reason that our hybrid scheduling makes a fair combination of both push and pull systems, which is required to improve the expected access-time. Figure 4.5 depicts the comparative view of the analytical results with the simulation results, for 1000 data items. The analytical results closely match with the simulation results for expected access time with almost $\sim 90\%$ and $\sim 93\%$ accuracy for $\lambda = 10$ and $\lambda = 20$ respectively. Thus, we can conclude that the performance analysis is capable of capturing the average system behavior with good accuracy. The little ($\sim 7\text{--}10\%$) differences exist because of the assumption of memory-less property associated with arrival rates and service times in the system.

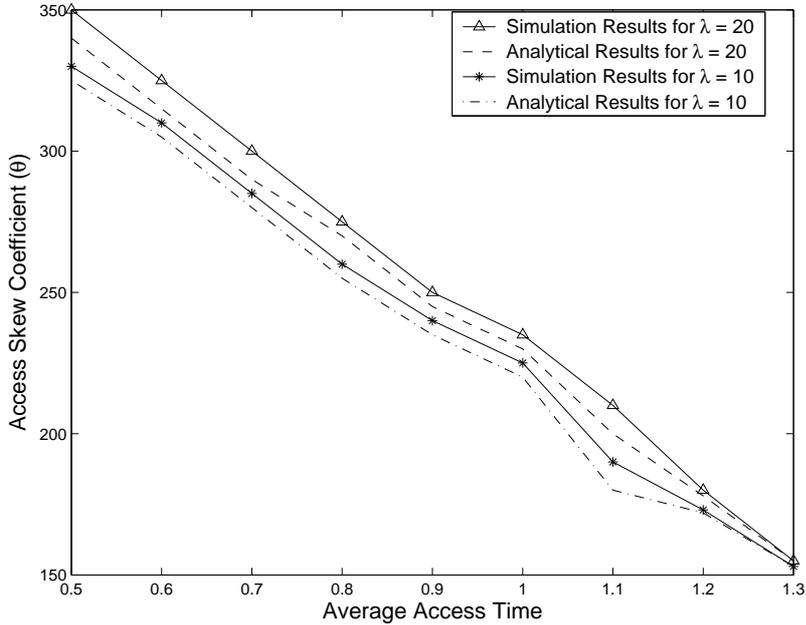


Figure 4.5: Comparison of Analytical and Simulation Results

4.2 Performance Guarantee in Hybrid Scheduling

While the performance evaluation of our new basic hybrid scheduling algorithm has already pointed out its significant gains in both response time and minimizing the value of the cut-off point when compared to existing algorithms and pure push-based scheduling, we now proceed to mention the complete version of our new algorithm [36] with performance guaranteed quality that our new scheduling scheme is capable to offer. Such performance guarantee is required to deliver, for example, the wireless voice and data packets within a precise time-frame of service, thereby ensuring a certain level of quality-of-service (QoS).

Essentially for all D possible values of the cut-off point, the server computes the expected hybrid waiting time $E[T_{hyb-access}]$. From now on, let $E[T_{hyb-access}(i)]$ denote such expected hybrid waiting time when i is the cut-off point value. These D expected waiting times are stored, one-at-a

time along with the index of the cut-off point that generates it, sequentially in a matrix V . That is, for all $1 \leq i \leq D$, $\mathbf{V}[i, 1] = [E[T_{hyb-access}(i)]$ and $\mathbf{V}[i, 2] = i]$. Moreover \mathbf{V} is maintained sorted with respect to the first component, i.e. the expected hybrid waiting time. With this structure, the server can extract the first element $\mathbf{V}[0]$ of this matrix in a single access, which will indicate in correspondence of which value K_0 of the cut-off point the minimum expected hybrid waiting time $\mathbf{V}[0, 1] = E[T_{hyb-access}(K_0)]$ is achieved. The server broadcasts $\mathbf{V}[0]$ from time to time, thereby informing the clients of the best performance it can provide. Moreover, the server continuously broadcasts the basic hybrid scheduling that corresponds to the cut-off point K in use we discussed in previous section. On the other side, when a client sends a request for any item j , it also specifies an expectation $\Delta(j)$ of its possible waiting time for item j . Indeed, $\Delta(j)$ reflects the nature of the application, and the tolerance of the client. For example, a client requesting for any real-time video application, will expect a time much lower than any client requesting data service-specific applications. Moreover, an impatient client could ask that its request is served in a time much lower than its moderate counterparts.

In order to accept a client request for item j with expectation $\Delta(j)$, the server estimates the expected waiting time for j at this current time instant using the values stored in matrix \mathbf{V} and the knowledge of the current cut-off point K in use for the hybrid scheduling algorithm broadcasted by the server. If the expected hybrid waiting time provided by the system is smaller or equal to the expectation time of the client's request, then the certain level of QoS expected by the client is guaranteed. Otherwise, the server checks whether the item j belongs to its current push set, that is if $j \leq K$. If this is true, it compares the client request deadline with the expected waiting time guaranteed by the Packed Fair Scheduling Queueing for the push part of the system, say $E[T_{PFS}(j)]$. Recall that such a value

Performance Guarantee in Hybrid Scheduling

```
1. for ( $i = 1$  to  $D$ ) do
2.     compute the average waiting time  $E[T_{hyb-access}(i)]$ ;
3.     sort all the values of  $E[T_{hyb-access}(1)], \dots, E[T_{hyb-access}(D)]$  and
store them in increasing order in a matrix  $\mathbf{V}$ 
4.     broadcast to the clients the min{affordable waiting time}  $\mathbf{V}[0]$ ;
do
5. accept the client's request for any item  $j$  with expected
waiting-time  $\Delta(j) \geq E[T_{hyb-access}(K)]$ , where  $K =$  current cut-off;
6. if (condition at line 5 is not verified and  $j \leq K$ )
    accept the client's request for any item  $j$  with expected
    waiting-time  $\Delta(j) \geq 2E[T_{PFS}(j)]$ , where  $E[T_{PFS}(j)]$  is the
    expected waiting time guaranteed by Packet Fair Scheduling;
7. if (both conditions at lines 5 and 6 are not verified) and
    ( $\Delta(j)$  is larger than expected waiting time stored in  $\mathbf{V}[0,1]$ )
8.     get the largest value of  $E[T_{hyb-access}(j)] \leq \Delta(j)$  from  $\mathbf{V}$ 
9.     adjust the cut-off point and restart new hybrid scheduling;
10. otherwise reject the request.
while (true)
```

Figure 4.6: Algorithm for Performance Guarantee in Hybrid Scheduling

is known and it is proportional to the space S_j between two instances of j in the Packed Fair Queueing Scheduling [19], and it is different from the overall expected waiting time of the server although it depends on the cut-off point in use. Now, if the expectation of the client $2E[T_{PFS}(j)]$ is smaller than or equal to $\Delta(j)$, the request can still be accepted and the performance guarantee. Note that the $E[T_{PFS}(j)]$ is doubled to take in the figure the fact that the system pulls one item between two consecutive pushed items. Otherwise, the request can be accepted only if the cut-off point is updated. Indeed, the server will perform a binary search on the matrix \mathbf{V} to look for a cut-off point value whose corresponding expected hybrid waiting time is the largest value smaller than or equal to $\Delta(j)$. Note that such a value always exists if $\mathbf{V}[0,1] \leq \Delta(j)$. Then, the cut-

off point is updated accordingly and the scheduling re-initialized. Note that the adjustment in push and pull sets results in some overheads, and in practice, the server may be forced to reject requests to avoid to pay such an overhead too frequently. Figure 4.6 provides a pseudo-code for this entire procedure of performance guarantee.

4.3 Summary

In this chapter we have improved our hybrid scheduling framework to make it adaptive with the system's behavior and provide certain level of performance guarantee. Instead of strict, sequential push and pull operation, the hybrid scheduling framework now probabilistically determines the number of consecutive push and pull operations based on the system's requirements. Subsequently, we propose a strategy to provide certain level of performance guarantee by meeting the clients' deadlines.

Chapter 5

Hybrid Scheduling with Client's Impatience

In most practical systems, clients often get impatient while waiting for the designated data item. After a tolerance limit, the client may depart from the system, thereby resulting in a drop of access requests. This behavior significantly affects the system performance, which needs to be properly addressed. There are also ambiguous cases which reflect the false situation of the system. Consider the scenario where a client gets impatient and sends multiple requests for a single data item to the server. Even if that particular data item is not requested by any other client, its access probability becomes higher. In existing systems, the server remains ignorant of this fact and thus considers the item as popular and inserts it into the push set or pull it at the expense of some other popular item. In contrast, our work [43] reduces the overall waiting time of the system taking care of such anomalies.

5.1 Hybrid Scheduling Algorithm

The major novelty of our strategy lies in its consideration for clients' impatience which is incorporated in two different ways, thereby leading to

two different strategies. Although the basics of both strategies are similar, the first one considers that the impatience of a client results in a departure from the system. This strategy is termed as *Hybrid Scheduling with Clients Departure*. Whereas, the second strategy considers the fact that a client's impatience compels it to send spurious requests for a particular data item, thereby creating an anomalous (ambiguous) situation in the system. We term this strategy as *Hybrid Scheduling with Anomalies*.

In general, the system begins with operating as a pure pull system providing on-demand service for every client. When the number of client's access request rate increases and broadcasting the same item to different clients causes downstream bandwidth wastage, the algorithm shifts to the hybrid mode. The items are now divided into two disjoint sets: the push set of cardinality K and the pull set of cardinality $D - K$. The items to be pushed are governed by *flat* round-robin scheduling. On the other hand, the item which maximizes stretch (max-request min-service time) is selected to be pulled by the server. Every push is followed by a pull, provided that the pull-set (queue) is not empty. If there are no items in the pull queue, then the server simply continues pushing the items using flat schedule. However, after transmitting each page the server attempts λ more access requests arriving into the system. If the request is for a push item, the server simply ignores the request as the item would be pushed anyway according to the broadcast schedule.

If the request is for a pull item, then the server first checks whether the request is for a new item or an already requested item. If it is for a new item, the item is inserted into the pull queue and its stretch value is calculated. Next, the server checks for the client's impatience and tolerance. The impatience is considered in the following two strategies as follows.

5.1.1 Hybrid Scheduling with Clients' Departure

If the request is for an existing item, the server checks whether one or more clients are getting impatient and losing their tolerance limit. Anticipating departures of such clients, the server drops their requests and stores their previous waiting time (departure time – arrival time). It then updates the stretch value of the data items in the pull queue considering only the request of existing clients which are not impatient. A pseudo-code of the strategy is depicted in Figure 5.1. The procedure *Take-Access-with-Drop()* considers λ more requests, process them and insert in the pull queue, after considering the number of requests dropped due to the client's departure. A pseudo-code of this procedure is shown in Figure 5.2.

```
HYBRID SCHEDULING with CLIENT's DEPARTURE;  
while true do  
begin  
Broadcast all the pages of an item, selected  
according to the flat scheduling;  
After broadcasting each page  
Take-Access-with Drop();  
if the pull-queue is not empty then  
    extract an item from the pull-queue  
    that optimizes the stretch;  
    clear the number of pending requests for  
    that item and pull it;  
Take-Access-with-Drop() /*procedure call */  
end;
```

Figure 5.1: Hybrid Scheduling with Client's Departure

5.1.2 Hybrid Scheduling with Anomalies:

While considering a request for an item that is already in the pull queue, the server checks for anomalies arising from spurious requests of impatient

```

Procedure: Take-Access-with-Drop();
Take  $\lambda$  more accesses;
if the request is for push items then
  ignore the requests;
if the request is for pull items then
  Compute the number of impatient clients
  leaving and number of clients remaining;
  insert the request for the pull item into
  the pull queue (with arrival time);
  update the stretch value of data items in
  pull queue based on number of remaining
  clients;

```

Figure 5.2: Take Access with Drop-requests

client(s) for a particular data item. While exceeding the tolerance limit, a single client can send a large number of requests for a particular data item, thereby making it *pseudo-popular*. In existing hybrid scheduling schemes, the server is ignorant of this fact and considers the item as a popular one, even if it is requested by a single client. In order to remove this anomaly the server now considers only unique requests for data items, i.e., if the request is from a new client, and not from the same client(s) who have already requested this item before. Thus, the system computes the unique requests by the clients, i.e., the effective number of requests for data item i . The stretch values of the items in the pull queue are now updated using these unique requests. A pseudo-code of this algorithm is shown in Figure 5.3. The procedure *Proc-Req-Anomalies()* takes λ more requests, process the requests and inserts them into the pull queue after removing the anomalies associated with the requests. The pseudo-code of this procedure is shown in Figure 5.4

The dynamics of the system often leads to changes in the arrival rate of the access requests, in other words in the access skew coefficient (θ). Hence,

```

HYBRID SCHEDULING with ANOMALIES;
while true do
begin
Broadcast all the pages of an item,
according to the flat scheduling;
After broadcasting each page
Proc-Req-Anomalies();
if the pull-queue is not empty then
    extract an item from the pull-queue
    that optimizes the stretch;
    clear the number of pending requests for
    that item and pull-it;
Proc-Req-Anomalies(); /* procedure call */
end;

```

Figure 5.3: Hybrid Scheduling with Anomalies

```

Procedure: Proc-Req-Anomalies();
Take  $\lambda$  accesses;
if the request is for push items then
    ignore the requests;
if the request is for pull items then
    if the same item is not requested
    by same client(s)
        insert the request for this pull item into
        the pull-queue (with arrival time);
        update the stretch value of the data
        items in pull-queue;

```

Figure 5.4: Process requests with Anomalies

the access probabilities for all data items are recalculated. Based on these new access probabilities, the cut-off point (K) is calculated dynamically. This needs dynamic shuffle of some items between the push and the pull-set. Whenever a client requires an item, it sends a request for that item to the server. The clients can request any item from the server. No matter

whether the item is currently being broadcasted or disseminated, the client simply passes its request for the interested item to the server and listens to the channel until its desired item is obtained. This procedure is highlighted in Figure 5.5.

```

Procedure CLIENT-REQUEST (i):
/* i : item the client is interested in
*/
begin
send to the server the request for item
i;
wait until listen for i on the channel
end

```

Figure 5.5: Algorithm at the Client Side

5.2 Performance Modeling and Analysis

In this section we analyze the performance of our hybrid scheduling algorithm. Recall that we have proposed two different schemes to incorporate client's impatience and accordingly we analyze the system performance by developing two different queuing models. However, the primary goal of both the analysis is to estimate the minimum expected waiting time (delay) of the hybrid system. Before proceeding further, let us enumerate the parameters and assumptions used.

5.2.1 Assumptions

1. The arrival rate in the entire system is assumed to obey the Poisson distribution with mean λ' . This includes the arrival rate in both push and pull systems. Although the arrival rate of the push system is assumed fixed, the departure of impatient clients and/or their spurious requests changes the arrival rate of the pull system at every step. The

initial arrival rate of the pull system is assumed to be λ . The pull queue contains data items which are yet to be served. Thus by the term pull system, we mean the items waiting in pull queue, together with the item(s) currently getting service.

2. The service times of both the push and pull systems are exponentially distributed. Again, the mean service time of push system is fixed, however, the clients' impatience changes the service time of the pull system. We represent the initial service time of pull system by μ_2 .
3. Let C , D and K respectively represent the maximum number of clients, total number of distinct data items, and the cut-off point. The server pushes K items while clients pull the remaining $(D - K)$ items. Thus, the total probability of items in the push- and pull sets are respectively given by $\sum_{i=1}^K P_i$ and $\sum_{i=K+1}^D P_i = (1 - \sum_{i=1}^K P_i)$, where P_i denotes the access probability of item i . Basically, it gives a probabilistic measure of item's popularity among the clients. We have assumed that the access probabilities follow the *Zipf's distribution* with *access skew-coefficient* θ , such that $P_i = \frac{(1/i)^\theta}{\sum_{j=1}^n (1/j)^\theta}$. Items are numbered from 1 to D and are arranged in the decreasing order of their access probabilities, i.e., $P_1 \geq P_2 \geq \dots \geq P_D$. Table 5.1 lists the symbols with their meaning used in the context of our analysis.

Let us now analyze the system performance for achieving the minimal waiting time. First, we discuss the model when the client loses its patience and leaves the system. Next, we discuss the system where an impatient client transmits spurious requests for a particular data item. As mentioned, this situation creates *anomaly* in the system, and the server needs to ignore such requests.

Table 5.1: Symbols Used for Performance Analysis

<i>Symbols</i>	Meanings
D	Maximum number of data items
C	Maximum number of clients
i	Candidate data item
K	Cut-Off Point separating push and pull sets
P_i	Access Probability of item i
L_i	Length of item i
λ'	Overall System Arrival Rate
λ	Initial Arrival Rate in pull queue
μ_1	Push Queue Service Rate
μ_2	Initial Service Rate in Pull Queue
$E[W_{pull}]$	Expected Waiting Time of Pull System
$E[W_{pull}^q]$	Expected Waiting Time of Pull Queue
$E[\mathcal{L}_{pull}]$	Expected Number of items in the Pull system
$E[\mathcal{L}_{pull}^q]$	Expected Number of items in the Pull queue

5.2.2 Client's Departure from the System

Here we assume that a client's impatience results in its departure from the system before the item is actually serviced. This impatience generally takes two forms [17]: (1) The reluctance of the customer to remain in the system is known as *reneging*; (2) Excessive reluctance might restrain the customer to even join the system, which is known as *balking*. These two behaviors significantly affect the arrival/service rate and average system performance. In our analysis, we have assumed the duration of the waiting time of a client (before leaving) to follow exponential distribution with mean $1/\tau$. If $\bar{\lambda}_m$ represents the request arrival rate for m^{th} data item, then $\bar{\lambda}_m = P_m\lambda$, where λ is the initial request arrival rate of the entire pull system. If the request arrives at time t and does not depart the system before servicing the m^{th} data at time Γ , then expected number of requests, $E[R_i]$, satisfied by transmission of m^{th} item is given by:

$$E[R_m] = \int_0^{\Gamma} \bar{\lambda}_m e^{-\tau(\Gamma-t)} dt$$

$$= \frac{P_m \lambda}{\tau} (1 - e^{-\tau \Gamma}) \quad (5.1)$$

Also, for Poisson arrival, the expected number of requests arriving in time period Γ is given by $\lambda \Gamma$. Thus, the expected number of drop requests, $E[R_d]$, is measured as:

$$\begin{aligned} E[R_d] &= \lambda \Gamma - E[R_m] \\ &= \lambda \Gamma - \frac{P_m \lambda}{\tau} (1 - e^{-\tau \Gamma}) \end{aligned} \quad (5.2)$$

Our next objective is to estimate the expected waiting time of our hybrid system considering the clients balking and reneging due to client's impatience.

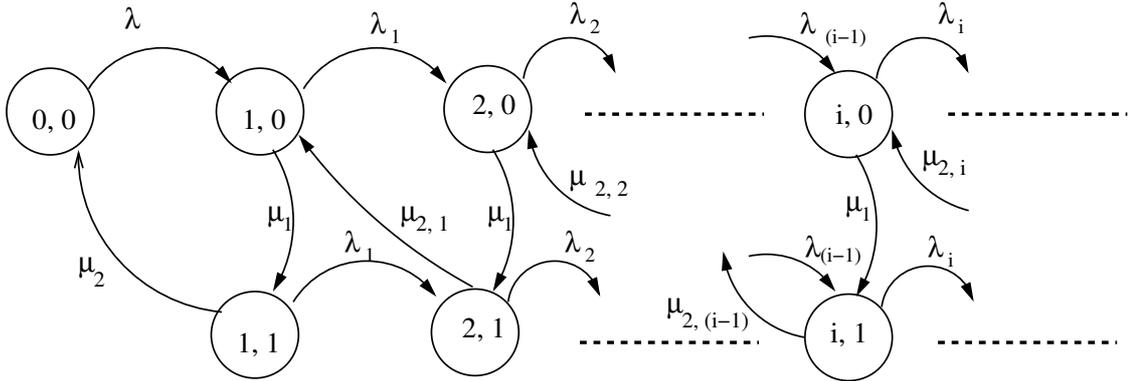


Figure 5.6: Performance Modelling of Our Hybrid System

Figure 5.6 illustrates the birth and death model of our system. For any variable i , the i^{th} state of the overall system is represented by the tuple (i, j) , where i represents the number of items in the pull-system and $j = 0$ (or 1) respectively represents whether the push-system (or pull-system) is being served. The arrival of a data item in the pull-system results in the transition from state (i, j) to state $(i+1, j)$, $\forall i \in [0, \infty]$ and $\forall j \in [0, 1]$. The service of an item results in transition of the system from state $(i, j = 0)$ to state $(i, j = 1)$, $\forall i \in [0, \infty]$. On the other hand, the service of an item

in the pull results in transition of the system from state $(i, j = 1)$ to the state $(i - 1, j = 0), \forall i \in [1, \infty]$. Note that, the arrival and service rates in the pull system are both different at each state. Naturally, the state of the system at $(i = 0, j = 0)$ represents that the pull-queue is empty and any subsequent service of the elements of push system leaves the system in the same $(0, 0)$ state. Obviously, state $(i = 0, j = 1)$ is not valid because the service of an empty pull-queue is not possible. The arrival rates at different states are now represented by $\lambda_0, \lambda_1, \dots, \lambda_i, \dots$, where $\lambda_0 = \lambda$. Furthermore, λ_i is different from $\bar{\lambda}_m$ discussed before. While $\bar{\lambda}_m$ represents the request arrival rate for m^{th} data item, λ_i denotes the total arrival rate of requests for all i items present in the system, i.e., $\lambda_i = \sum_{m=0}^i \bar{\lambda}_m$. Similarly, the service rates at different states are denoted by $\mu_{2,j}$ where $1 \leq j \leq n$ and $\mu_{2,1} = \mu_2$.

In the steady-state, using the flow-balance conditions of *Chapman-Kolmogorov's* equation [17], the initial system-behavior is represented by:

$$p(0, 0) \lambda = p(1, 1) \mu_2 \quad (5.3)$$

where $p(i, j)$ represents the probability of state (i, j) . The overall behavior of the system for push (upper chain in Figure 5.6) and the pull system (lower chain) are given by the following two generalized equations:

$$p(i, 0)(\lambda_i + \mu_1) = p(i - 1, 0)\lambda_{i-1} + p(i + 1, 1)\mu_{2,i+1} \quad (5.4)$$

$$p(i, 1)(\lambda_i + \mu_{2,i}) = p(i, 0)\mu_1 + p(i - 1, 1)\lambda_{i-1} \quad (5.5)$$

Balking [17] is generally estimated by using a series of monotonically decreasing functions of the system size multiplying by the initial arrival rate, λ . If b_i is the balking function at i^{th} state, then $\lambda_i = b_i \lambda$, where $0 \leq b_{i+1} \leq b_i \leq 1, (\forall i > 0, b_0 = 1)$. The most practical discouragement (balking) function is $b_i = e^{-i\alpha}$, where α is a constant. This takes the queue size into account and discourages the customers from joining in large-sized queues.

However, in practical systems, the discouragement does not always arrive from excessive queue sizes. These customers might instead join the system and continuously retain the prerogative to *renege* if the waiting time is intolerable. This renegeing function $r(i)$ [17] at i^{th} state is defined by:

$$r(i) = \lim_{\Delta t \rightarrow 0} \frac{Pr[\text{unit reneges during } \Delta t]}{\Delta t} \quad (5.6)$$

The service rate of pull queue now takes the form: $\mu_2 = \mu_2 + r(i)$. A good possibility of the renegeing function is: $r(i) = e^{i\alpha/\mu_2}$. Note that both balking and renegeing functions are assumed to follow exponential distribution, which is in accordance with the distribution obeyed by request's waiting time.

From Equations (5.4) and (5.5) we get,

$$\begin{aligned} p(i, 0)(e^{-\alpha i} \lambda + \mu_1) &= p(i-1, 0)\lambda e^{-\alpha(i-1)} + p(i+1, 1)\mu_2 + e^{(i+1)\frac{\alpha}{\mu_2}} \\ p(i, 1)\lambda e^{-\alpha i} + p(i, 1)\mu_2 &+ p(i, 1)e^{\alpha\frac{i}{\mu_2}} = p(i, 0)\mu_1 + p(i-1, 1)e^{-\alpha(i-1)} \end{aligned} \quad (5.7)$$

The most efficient way to solve of Equation (5.7) is using *Z-transforms* [17]. From the definition of *z-transforms*, the resulting solutions are of the form:

$$P_1(z) = \sum_{i=0}^C p(i, 0) z^i \quad \text{and} \quad P_2(z) = \sum_{i=0}^C p(i, 1) z^i. \quad (5.8)$$

Using subsequent *Z-transforms*, Equation (5.7) yields:

$$\begin{aligned} &\lambda \left[P_1 \left(\frac{z}{e^\alpha} \right) - p(0, 0) \right] + \mu_1 [P_1(z) - p(0, 0)] \\ &= \lambda z \left[P_1 \left(\frac{z}{e^\alpha} \right) \right] + \frac{1}{z} [P_2(z) - p(0, 1) - p(1, 1)] \\ &+ \frac{1}{z} \left[P_2 \left(z e^{\frac{\alpha}{\mu_2}} \right) - p(0, 1) - p(1, 1) \right] \end{aligned} \quad (5.9)$$

Similarly, transforming Equation (5.7) leads to:

$$\lambda P_2\left(\frac{z}{e^\alpha}\right) + P_2\left(ze^{\frac{\alpha}{\mu_2}}\right) = \mu_1 P_1(z) - p(0,0) + zP_2\left(\frac{z}{e^\alpha}\right) \quad (5.10)$$

Now, putting $z = 1$ in Equation (5.9), we can obtain the probability $p(0,0)$ of the idle state as:

$$\begin{aligned} & \lambda \left[P_1\left(\frac{1}{e^\alpha}\right) - p(0,0) \right] + \mu_1 [P_1(1) - p(0,0)] \\ &= \lambda \left[P_1\left(\frac{1}{e^\alpha}\right) \right] + \mu_2 [P_2(1) - p(1,1)] + P_2\left(e^{\frac{\alpha}{\mu_2}}\right) - p(1,1) \\ p(0,0) &= \frac{\mu_2 \rho - \mu_1(1 - \rho) + \frac{\rho}{1 - e^{\frac{\alpha}{\mu_2}}}}{\frac{\lambda}{\mu_2} - \mu_1} \end{aligned} \quad (5.11)$$

Deriving closed form solutions of Equations (5.9) and (5.10) to evaluate the state probabilities seems not possible. Instead we measure the expected performance of the overall system. In order to estimate the average number of items in the pull system, Equation (5.9) is differentiated (at $z = 1$). Now, the occupancy of push and pull states are respectively given by $P_1(1) = \sum_{i=0}^{\infty} p(i,0) = 1 - \rho$ and $P_2(1) = \sum_{i=0}^{\infty} p(i,1) = \rho$, where $\rho = \frac{\lambda_{eff}}{\mu_{eff}} = \frac{\sum_{i=0}^{\infty} \lambda_i p(i,1)}{\sum_{i=1}^{\infty} \mu_{2,i} p(i,1)}$. Differentiating Equation (5.9) and using these values of $P_1(1)$ and $P_2(1)$, we get

$$\begin{aligned} & \mu_2 \frac{dP_2(z)}{dz} + \frac{dP_2}{dz}\left(ze^{\frac{\alpha}{\mu_2}}\right) = \mu_1 P_1(1) + \mu_1 \frac{dP_1}{dz} \\ & - (\lambda + \mu_1) \frac{\mu_1 \rho - \mu_1(1 - \rho) + \frac{1}{1 - e^{\frac{\alpha}{\mu_2}}}}{\lambda/\mu_2 - \mu_1} - \\ & \lambda P_1(1/e^\alpha) - \lambda \frac{dP_1}{dz}\left(\frac{1}{e^\alpha}\right) + 2\lambda P_1(1/e^\alpha) + \lambda P_1(1/e^\alpha) \\ E[\mathcal{L}_{pull}] &= \frac{dP_2(z)}{dz}\Big|_{z=1} = \left(\mu_1 + \frac{1}{1 - e^{\frac{\alpha}{\mu_2}}} \right)^{-1} \\ & \left[\mu_1 \rho + \mu_1 E[\mathcal{L}_{push}] - (\mu_1 + \lambda) \frac{\mu_1 \rho - \mu_1(1 - \rho) + \frac{\rho}{1 - e^{\frac{\alpha}{\mu_2}}}}{\frac{\lambda}{\mu_2} - \mu_1} \right] \end{aligned}$$

$$+\lambda E[\mathcal{L}_{push}]e^{\alpha/mu_2}, \text{ (where } E[\mathcal{L}_{push}] = \frac{dP_1(z)}{dz}|_{z=1}) \quad (5.12)$$

Once we have the expected number of items in the pull system from Equation (5.12), using Little's formula [17], we can easily estimate the average waiting time of the system ($E[W_{pull}]$), average waiting time of the pull queue ($E[W_{pull}^q]$) and expected number of items ($E[\mathcal{L}_{pull}^q]$) in the pull queue as follows:

$$E[W_{pull}] = \frac{E[\mathcal{L}_{pull}]}{\lambda}, E[\mathcal{L}_{pull}^q] = E[\mathcal{L}_{pull}] - \frac{\lambda}{\mu_2} \text{ and } E[W_{pull}^q] = E[W_{pull}] - \frac{1}{\mu_2}.$$

Since the push system is governed by flat scheduling, the average cycle time of the push system is given by: $\frac{K}{2(1-\rho)\mu_1} \sum_{i=1}^K P_i$. Thus, the overall minimum expected access-time, ($E[T_{hyb-acc}]$), of our hybrid system is:

$$E[T_{hyb-acc}] = \frac{K}{2(1-\rho)\mu_1} \sum_{i=1}^K P_i + E[W_{pull}] \sum_{i=K+1}^D P_i \quad (5.13)$$

This gives a suitable measure of the performance of our hybrid, heterogeneous system when the clients get impatient and leave the system at certain intervals. Our next objective is to analyze the performance of the system, when the impatience does not force the clients to leave the system, but makes them to transmit spurious requests for the same data item.

5.2.3 Anomalies from Spurious Requests

As discussed earlier, the anomaly arises from the clients making multiple, spurious requests for the same data item, thereby making the particular item *pseudo-popular*. In other words, the item might not be popular (i.e., not requested by many clients), but the server is ignorant of this fact and considers it to be popular. The objective of the hybrid scheduling is to remove this anomalous behavior and develop a performance analysis to obtain an estimate of average behavior of the real system. Intuitively, the

spurious requests change the arrival rate in the pull system at every state. However, the service rate of both push and pull systems remains constant. Thus, the overall model of the system remains similar to the birth and death process as shown in Figure 5.6, but with different measures of λ_i and all $\mu_{2,i} = \mu_2$. Naturally, the state space and basic equations of the model is similar to Equations (5.3–5.5). However, we need to estimate the different arrival rates at different states.

A careful look into this system reveals that the basic idea behind removal of anomaly is *to ignore multiple spurious requests for a data item sent by the same set of clients*. While modelling and analyzing such a system is extremely complex, quite satisfactory results can be obtained by not considering the individual client's role explicitly. Hence, for performance analysis, we consider the system as *ignoring the multiple, spurious requests for a particular data item as a whole*. At this point of time we explain the behavior of the system characterized by the presence of data items. Note that every state in Figure 5.6 represents the number of items present in that state. Hence, in state (1, 0) and (1, 1) it could be any one of the D items present. Similarly, in state 2 any two items could be present, with the condition that an item already present (requested) will not be considered for another request. This procedure goes on for all the following states. Thus, in every state we consider unique data items requested by clients. The probability that a requested item will not be requested again, is given by: $\sum_{j=1}^i \prod_{k=1, k \neq j}^i P_j P_k$. Hence, the arrival rate in the state that contains i items, is given by:

$$\begin{aligned}
 \hat{\lambda}_i &= \lambda \sum_{j=1}^i \prod_{k=1, k \neq j}^i P_j P_k \\
 &= \lambda \left(i! \sum_{j=1}^n P_j \sum_{k=j}^{n-i+1} [P_{k+1} P_{k+2} \dots P_{k+i-1}] \right) \\
 &\quad (\text{as } P_j P_k = P_k P_j)
 \end{aligned} \tag{5.14}$$

Using suitable Z-transform of Equation (5.4) and (5.5) we get,

$$\begin{aligned}\hat{P}_2(z) &= \frac{1}{\mu_2}[z\hat{P}_1(z)(\hat{\lambda}_i + \mu_1)] - \frac{(\hat{\lambda}_i + \mu_1)zp(0,0)}{\mu_2} \\ &+ p(1,1) - \frac{z^2\hat{P}_1(z)\hat{\lambda}_{i-1}}{\mu_2}\end{aligned}\quad (5.15)$$

In order to obtain the probability $p(0,0)$ of the idle state, we evaluate the expression at $z = 1$. Indeed, the occupancy of the push and pull states are still the same. Thus, $\hat{P}_2(1) = \rho$ and $\hat{P}_1(1) = 1 - \rho$, where $\rho = \frac{\sum_{i=0}^{\infty} \lambda_i p(i,1)}{\mu_2}$. Thus we have,

$$\begin{aligned}\hat{P}_2(1) &= \frac{(\hat{\lambda}_i + \mu_1)}{\mu_2}\hat{P}_1(1) - \frac{(\hat{\lambda}_i - \hat{\lambda}_0 + \mu_1)}{\mu_2}p(0,0) - \frac{\hat{P}_1(1)\hat{\lambda}_{i-1}}{\mu_2} \\ \rho &= \frac{(\hat{\lambda}_i + \mu_1)}{\mu_2}(1 - \rho) - \frac{(\hat{\lambda}_i - \hat{\lambda}_0 + \mu_1)}{\mu_2}p(0,0) - \frac{\hat{\lambda}_{i-1}}{\mu_2}\hat{P}_1(1) \\ p(0,0) &= \left[\frac{\hat{\lambda}_i + \mu_1}{\mu_2}(1 - \rho) - \rho - \frac{\hat{\lambda}_{i-1}}{\mu_2}(1 - \rho) \right] \left(\frac{\mu_2}{\hat{\lambda}_i - \hat{\lambda}_0 + \mu_1} \right)\end{aligned}\quad (5.16)$$

where $\hat{\lambda}_i$ is given by Equation (5.14). In order to get an estimate of the average system performance, we differentiate Equation (5.15) to estimate the expected number of elements in the pull system.

$$\begin{aligned}\frac{d\hat{P}_2(Z)}{dZ} &= \frac{\hat{\lambda}_i + \mu_1}{\mu_2} \left[\hat{P} - 1(Z) + Z \frac{d\hat{P}_1(Z)}{dZ} \right] \\ &- \frac{\hat{\lambda}_i + \mu_1}{\mu_2} p(0,0) - \frac{2Z\hat{P}_1(Z)\hat{\lambda}_{i-1}}{\mu_2} - \frac{Z^2}{\mu_2} \frac{d\hat{P}_1(Z)}{dZ} \hat{\lambda}_{i-1} \\ \frac{d\hat{P}_2(Z)}{dZ} \Big|_{Z=1} &= \frac{\hat{\lambda}_i + \mu_1}{\mu_2} p(0,0) - \frac{2\hat{\lambda}_{i-1}}{\mu_2} \hat{P}_1(1) - \frac{\hat{\lambda}_{i-1}}{\mu_2} \frac{d\hat{P}_1}{dZ} \Big|_{Z=1} \\ E_a[\mathcal{L}_{pull}] &= \frac{\hat{\lambda}_i + \mu_1}{\mu_2} [1 - \rho - E[\mathcal{L}_{push}]] - \frac{\hat{\lambda}_i + \mu_1}{\mu_2} p(0,0) \\ &- \frac{2\hat{\lambda}_{i-1}}{\mu_2} \rho - \frac{\hat{\lambda}_{i-1}}{\mu_2} \rho\end{aligned}\quad (5.17)$$

Subsequently, using Little's formulae and combining the expression for waiting time of push system, the expected access-time, $E_a[T_{hyb-acc}]$, of our hybrid system which considers anomalies is obtained as:

$$E_a[T_{hyb-acc}] = \frac{K}{2(1-\rho)\mu_1} \sum_{i=1}^K P_i + E_a[W_{pull}] \times \sum_{i=K+1}^D P_i, \quad (5.18)$$

where $E_a[W_{pull}] = \frac{E_a[\mathcal{L}_{pull}]}{\lambda}$.

5.3 Simulation Experiments

In this section we validate the performance of our hybrid system through simulation experiments developed separately for both the strategies – hybrid scheduling with client's departure and hybrid scheduling with anomalies. While the primary goal of hybrid scheduling with anomalies is to reduce the expected access time, the hybrid scheduling with client's departure also considers reducing the service drop, apart from minimizing the expected access time. Before presenting the details of simulation results, we enumerate the salient assumptions and parameters used in our simulation.

1. The simulation experiments are evaluated for a total number of $D = 1000$ data items.
2. The overall arrival rate λ' is varied between 1–4 arrivals per unit time. The value of μ_1 and μ_2 is estimated as: $\mu_1 = \sum_{i=1}^K (P_i \times L_i)$ and $\mu_2 = \sum_{i=K+1}^D (P_i \times L_i)$ where P_i and L_i are the access probability and length of data item i , respectively.
3. The length of data items are varied from 1 to 5.
4. In order to keep the access probabilities of the items from similar to very skewed, θ is dynamically varied from 0.20 to 1.40.

- To compare the performance of our hybrid scheduling strategy with client's impatience, we have chosen the work in [24], as according to our knowledge, this is the only existing broadcast scheme which considered client's impatience.

In the following, we discuss a series of simulation results to demonstrate the efficiency of our two hybrid scheduling strategies. First we look into the results considering the client's departure (arising from impatience) from the system. Then we discuss the situation where client's impatience gives rise to anomalous behavior.

5.3.1 Hybrid Scheduling with Client's Departure

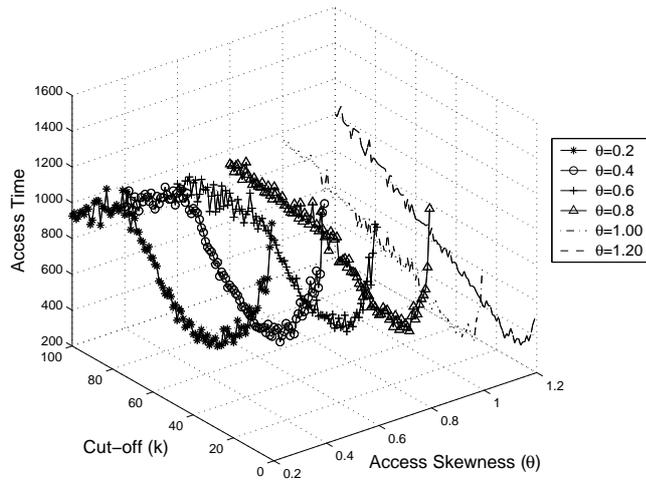


Figure 5.7: Expected Access Time with Cutoff Point

Figure 5.7 demonstrates the variation of expected access time with cutoff-points (K) for different values of access skewness, θ . For all values of θ , with increasing K the expected access time initially decreases up to a certain point and then increases again. The reason is that with lower values of K , the access time for push items are pretty low while those for pull items are very high. The scenario gets reversed when the value of K

is pretty high. The curve for the expected access time takes a bell-shaped form, with the minimum value obtaining for certain cutoff-point, termed as optimal cutoff.

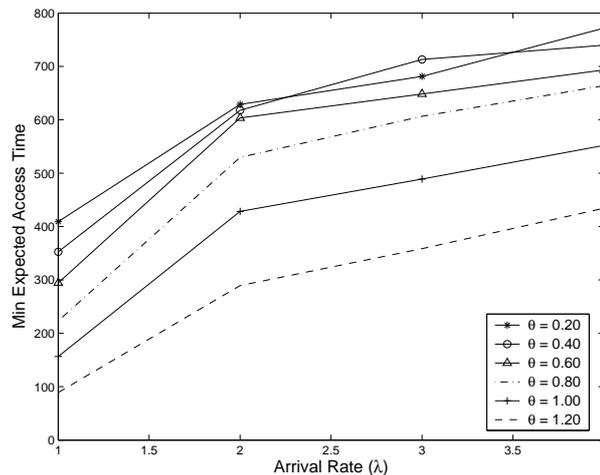


Figure 5.8: Minimum Expected Access Time with Arrival Rates

The different arrival rates of data items have significant impact on the minimum expected access time achieved by the system. Figure 5.8 shows that for different access skewness and with increasing arrival rates, the expected access time increases. For an arrival rate of 1 and 4, the average access time is in the range 100–400 and 400–750 time units respectively.

Next we analyze the variation of the cutoff point with access skewness for different arrival rates. This is necessary to get a clear picture of the system dynamics, as the cutoff point plays the major role to minimize the expected access time. Figure 5.9 shows that the value of cutoff point decreases with increasing values of access skewness, θ . For example, $K = 300$ – 500 for lower skewness ($\theta \leq 0.6$) and $K = 100$ – 150 for higher skewness ($\theta \geq 1.00$). The reason is that with increasing skewness, the items get more skewed and number of popular items decreases. Hence, fewer number of items are pushed, thus decreasing the cutoff point.

One major objective of our proposed hybrid scheduling is to reduce the

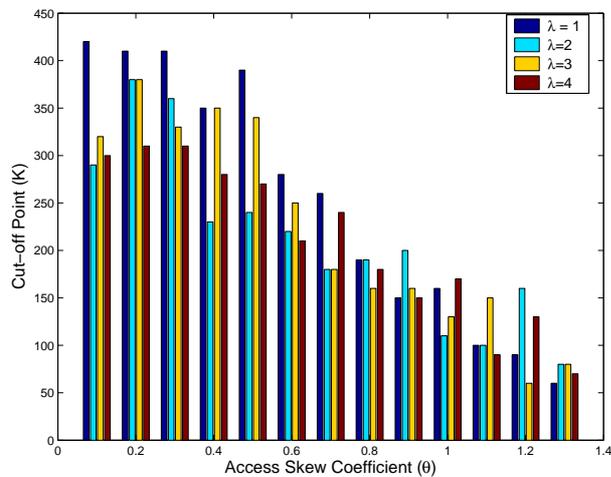


Figure 5.9: Variation of Cutoff Point

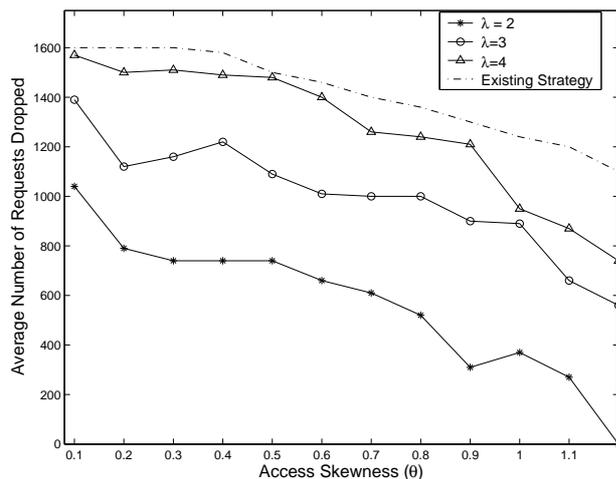


Figure 5.10: Average Number of Requests Dropped

dropped requests arising from client's impatience. Figure 5.10 depicts the average number of requests dropped with access skewness for different arrival rates. The performance is compared with the existing strategy [24] for client's impatience in data broadcasting with an unit arrival rate. As expected, the number of drop-requests increases with increasing arrival rates. However, for all arrival rates the number of drop requests is significantly lower than the number of drop-requests in existing work. This is true even

for higher arrival rates $\lambda' \geq 2$. This points out the efficiency of our hybrid scheduling strategy while considering client's departure due to impatience.

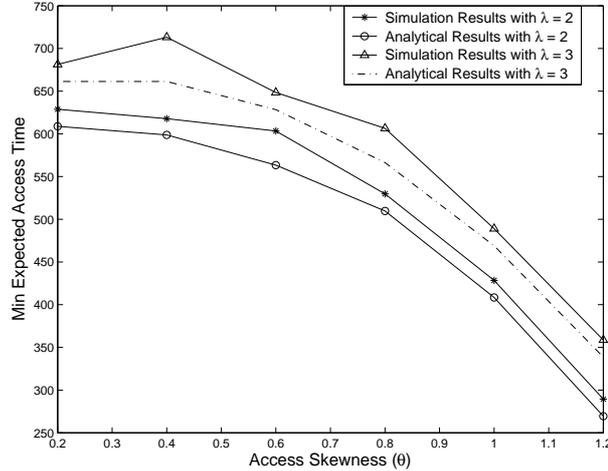


Figure 5.11: Comparison of Analytical and Simulation Results

Figure 5.11 provides the comparative view between analytical and simulation results for hybrid scheduling with client's departure. The simulation results closely match with the analytical results. The minor $\sim 8\%$ difference is primarily due to the fact that analytical results only capture an approximate average value.

5.3.2 Hybrid Scheduling with Anomalies

In this section, we discuss the simulation results for hybrid scheduling where the clients' impatience does not compel them to leave the system, but makes them transmit multiple request for the same data item, thus generating an anomaly in the system.

Figure 5.12 delineates the variation of expected access time with cutoff point for different values of access skewness. The variation of this access time is similar to Figure 5.7, and takes a bell-shaped form, i.e., the expected access time first decreases up to a certain point and then starts increasing.

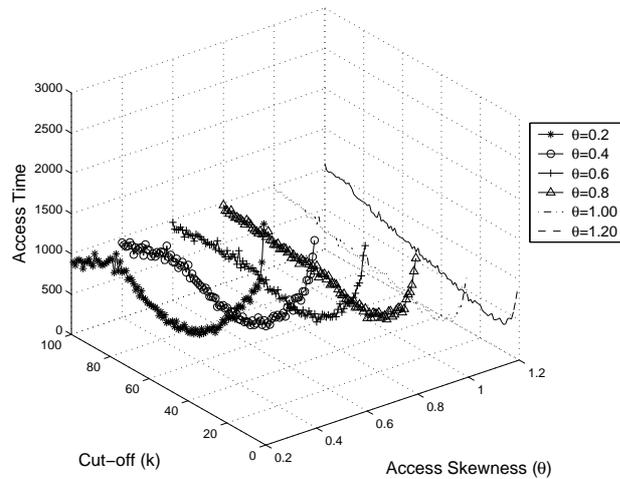


Figure 5.12: Variation of Expected Access Time with Cutoff-point

The optimal value of K is chosen to get the minimum expected access time for hybrid scheduling with anomalies.

The changes in the expected access time with different arrival rates is shown in Figure 5.13 for different values of access skewness. The increase in access skewness results in lower expected access time for all values of arrival rates. For items of unit length, the expected access time lies in the range 150–400 time units. For items of length 4, the expected access time is ~ 50 –110 time units.

The change in minimum expected access time with different values of access skewness and item-length is depicted in Figure 5.14. The waiting time is minimized (100 time units) for items of unit length and higher values of access skewness.

Finally, we investigate into the dynamics of cutoff point with different access skewness and arrival rates. Figures 5.15 and 5.16 show the variation of cutoff point with access skewness for different values of arrival rates and item lengths, respectively. For higher skewness, the cutoff decreases, thereby allowing more items in the pull queue and less items to be pushed. This is performed to achieve the minimum expected access time of the

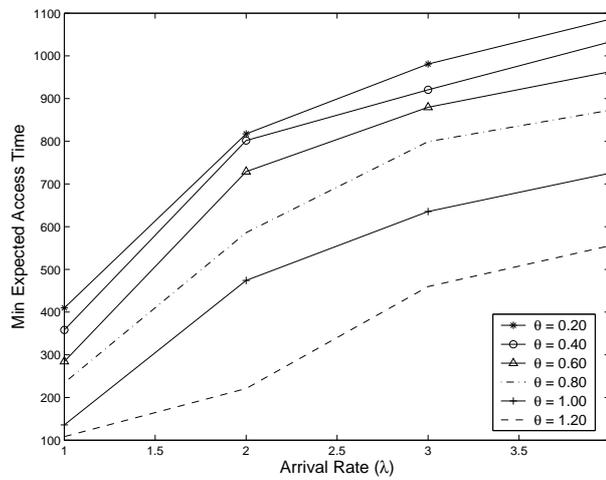


Figure 5.13: Minimum Expected Access Time with Arrival Rates

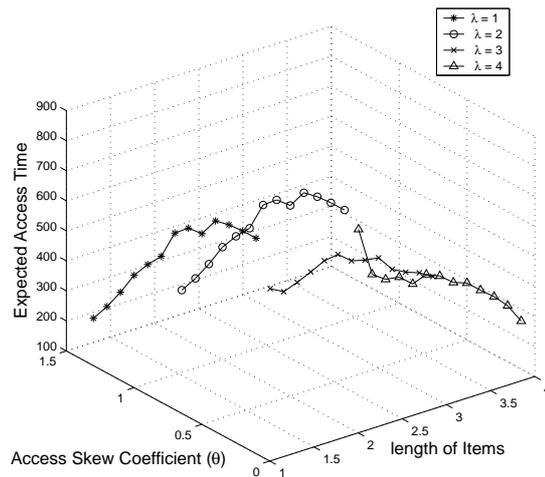


Figure 5.14: Expected Access Time with Item-length

system.

Figure 5.17 provides the comparative view between analytical and simulation results in hybrid scheduling with anomalies. The simulation results closely match (90%) with the analytical results. The minor difference is again attributed to the approximate nature of the analysis.

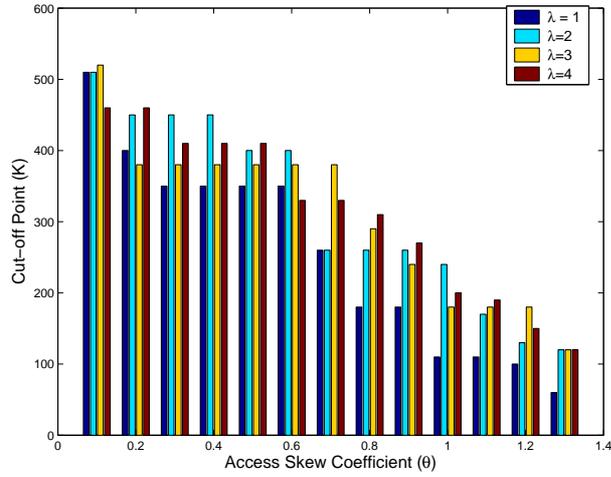


Figure 5.15: Variation of Cutoff point with Arrival Rates

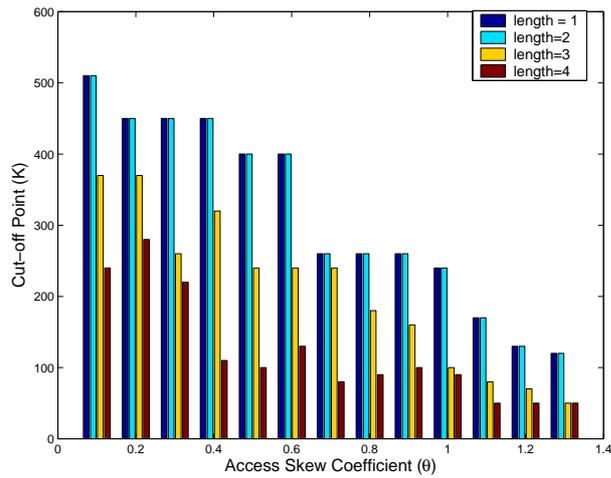


Figure 5.16: Variation of Cutoff point with Item-length

5.4 Summary

In this chapter we have enhanced our hybrid scheduling framework to make it more practical and close to real systems. In real systems the clients often get impatient which might result in two different scenarios. An impatient client might leave the system. Excessive impatience might lead to the client's declination in re-joining the system again. On the other hand, an

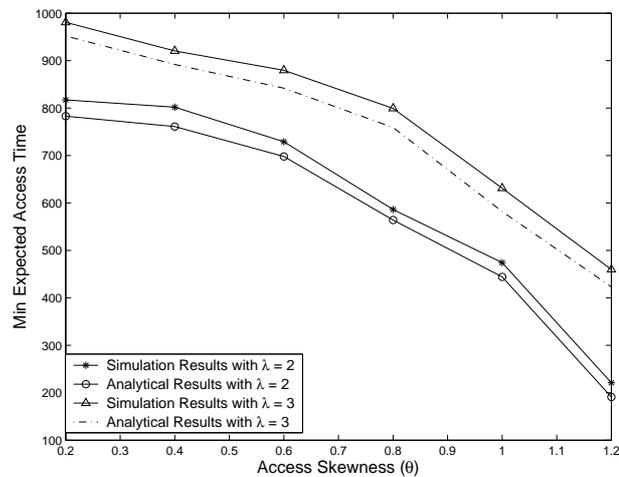


Figure 5.17: Comparison of Analytical and Simulation Results

impatient client can send multiple requests for the same item (the item it wants), thereby increasing that item's popularity. The server (system) might be ignorant of this fact, and can consider the item as a popular one. This raises an anomaly in the system. In this chapter we have enhanced our hybrid scheduling framework to cope up with clients' impatience to resolve the situation arising due to clients' departure and spurious requests (anomalies).

Chapter 6

Dynamic Hybrid Scheduling with Request Repetition

In this chapter we propose a dynamic hybrid scheduling [39], where any new request for a pull item is kept in the pull queue. However, the clients' impatience resulting from their prolonged waiting for any item, or a new requests for the same data item by another client often makes them to transmit repeated requests. The server keeps these repeated requests in the *repeat-attempt (retrial)* queue, thereby distinguishing such requests from the new requests arriving in the pull queue. At any instance of time the item to be serviced is selected by using *stretch* (i.e, *max-request min-service-time first*) optimal scheduling algorithm. The service of an item from the pull queue needs to consider the service of the instances of same items from the repeat-attempt queue also. Using a multi-dimensional Markov model the average performance of the overall heterogenous, hybrid scheduling system is derived.

6.1 Repeat-Attempt Hybrid Scheduling Scheme

Figure 6.1 highlights the overview of a *repeat-attempt system*. In the conventional communication, any request which finds the terminal busy is put

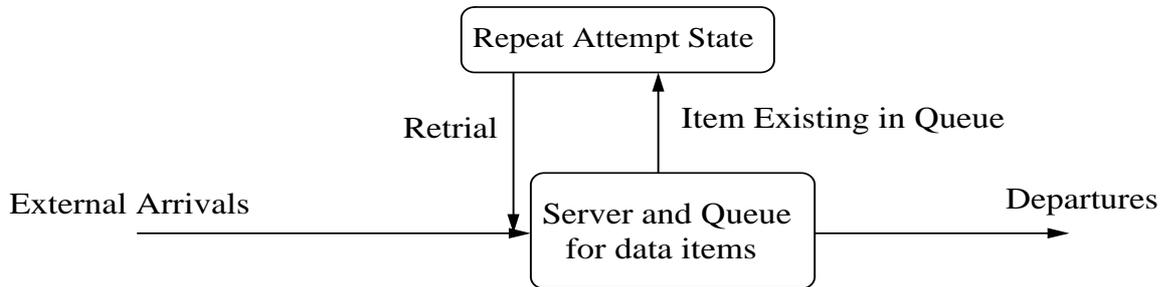


Figure 6.1: Overview of Repeat Attempt System

on the waiting queue. In a repeat-attempt model however, a request which finds the server busy checks whether the item is in the waiting queue. If not, the item is kept in the waiting queue. If the item is already in the waiting queue, it is stored in the repeat-attempt queue. This forms the basis of our newly-proposed repeat-attempt hybrid scheduling system. The database at the server consists of a total number of D distinct, heterogeneous items, out of which K items are pushed and the remaining $(D - K)$ items are pulled. The access probability P_i of an item i , i.e., the popularity of the items amongst the clients, is governed by the Zipf's distribution and depends on the access skew-coefficient (θ). From time to time the value of θ is changed dynamically for our hybrid system, thus varying P_i of all items and hence varying the size of the push and the pull sets dynamically.

The server maintains the database of all variable-length items. Periodically the server pushes the data items using a broadcast schedule. We have used the Packet Fair Scheduling (PFS) principle [19], which schedules the data items in an order such that two consecutive instances of the same data items are always equally spaced. When a client needs an item i , it sends to the server its request for item i and waits until it listens for i on the channel. If the request is for a push item, the server simply ignores the request as the item will be pushed according to the PFS algorithm. However, if the request is for a pull item, then the server first checks whether it

is a new item-request from a client or it is a request for the same data item by another client. If it is a request for a new item, it inserts the request into the pull queue with the arrival time and updates its stretch value. On the other-hand, if the request is not a new one, i.e., some other client has already requested the item, the server considers it as a *repeat attempt* from an impatient client, inserts the item into the repeat-attempt (retrial) queue and updates its stretch-value. After every push, if the pull queue is not empty, the server chooses one item based on optimal stretch value, i.e., the item having *max-request min-service-time* value from the pull-queue. It now pulls that item and clears the pending requests for that item in the pull-queue. Subsequently, the server now checks the repeat-attempt queue and clear the requests associated with the instances of the same item. Figure 6.2 provides the pseudo-code of the repeat-attempt, heterogeneous hybrid scheduling algorithm executing at the server-side, where the procedure *Access and pull()* is depicted in Figure 6.3.

6.2 Performance Analysis of the Hybrid Repeat Attempt System

In normal pull-based scheduling strategy, the clients send explicit request to the server and the server queues the requests. The item with maximum requests or maximum stretch (request/square of length) is selected for service. However, in real systems often the clients are *impatient*, i.e., they often send multiple requests for a data item while it is not being serviced. Similarly, if a data item is already requested by a client and is waiting for service, and another client requests the same data item, the item is also considered as repeat-attempt item. In these scenarios, the data items having multiple requests are assumed to be in a new state, termed *repeat attempt state*.

```

Procedure Hybrid Scheduling with
    Retrials;
while (true) do
begin
    Broadcast all pages of an item,
    selected according to the PFS;
    Access and pull();
    if (pull-queue is not empty) then
        extract an item, from pull
        queue, that optimizes stretch;
        if (tie)
            extract the item with the
            smallest index;
        clear the number of pending
        requests for this item in the
        pull queue;
        clear the pending requests for
        the instance of the same item
        in the repeat-attempt queue;
        pull the particular item;
    Access and pull();
end;

```

Figure 6.2: Hybrid Scheduling Algorithm with Repeat-Attempts

We have assumed Poisson's arrival and exponential service of the items to make the analysis mathematically tractable. Figure 6.4 shows the schematic diagram of such a multi-dimensional Markov model representing the repeat-attempt hybrid system. Any state of the system is represented by (x, y, z) , where x represents number of unique items in the pull queue ($0 \leq x \leq D - K$) and y represents number of repeat-attempt items in the repeat-attempt queue and $z = 0$ (or 1) represents push (or pull) system

```

Procedure Access and Pull();
while (true) do
begin
    take a specific number of accesses
    after broadcasting each page;
    if(the request is for push-item)
        ignore the request;
    else-if(the request is for pull-item)
        if(new request)
            insert the request into the
            pull queue with arrival time;
        else
            mark the request as a
            repeat-attempt;
            insert the request into the
            repeat-attempt queue;
end;

```

Figure 6.3: Access and Pull Scheduling

is currently under operation. The average arrival rate of the pull queue is assumed as λ . On the other hand, the arrival in the repeat-attempt queue is assumed to be directly proportional of the number of items present in the pull queue. Thus, the arrival rate in the repeat-attempt queue is taken as $x\xi\lambda$, where ξ is the scaling factor based on per item's average repeat attempt probability. We denote the transitional probability associated with transition from any state (x, y, z) to any another state (x', y', z') by $P_{(x,y,z);(x',y',z')}$. A careful insight into the system, shown in Figure 6.4 demonstrates the following major transitions:

1. There is only single transition possible from initial (idle) state $(0, 0, 0)$. This happened with probability $P_{(0,0,0);(1,0,0)}$ during the arrival of any

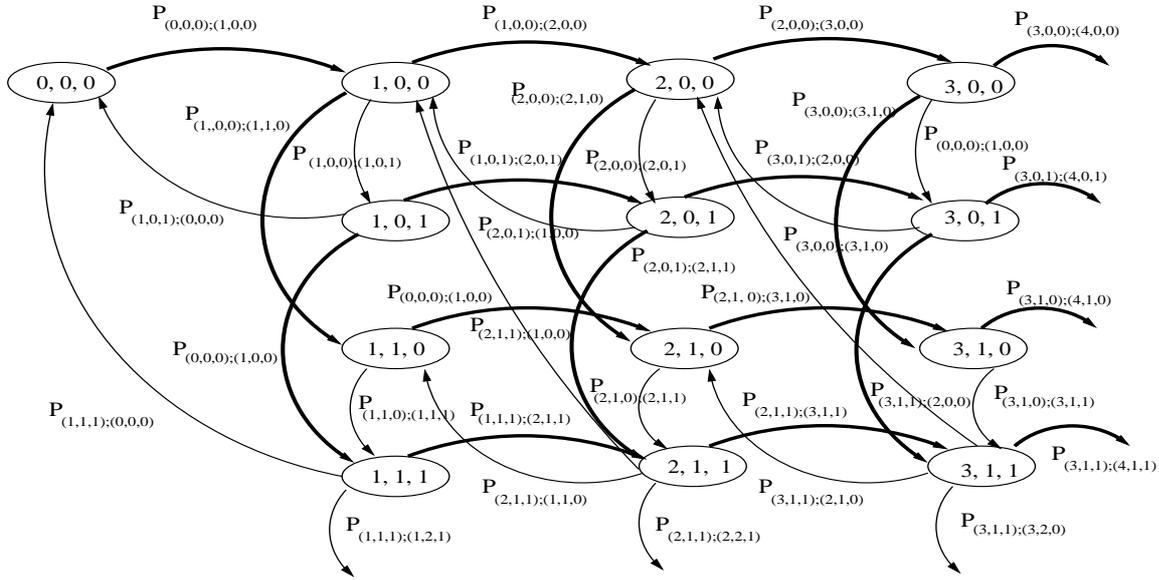


Figure 6.4: Repeat Attempt Markov Model of Hybrid Scheduling

item in the pull system.

2. Arrival of any item in the pull queue results in transition of state in both the push and pull system from $(x, y, 0)$ and $(x, y, 1)$ to $(x+1, y, 0)$ and $(x+1, y, 1)$ with probabilities $P_{(x,y,0);(x+1,y,0)}$ and $P_{(x,y,1);(x+1,y,1)}$ respectively.
3. Similarly, arrival of any item in the repeat-attempt queue results in transition of states in the repeat-attempt system from $(x, y, 0)$ and $(x, y, 1)$ to $(x, y+1, 0)$ and $(x, y+1, 1)$ with probabilities $P_{(x,y,0);(x,y+1,0)}$ and $P_{(x,y,1);(x,y+1,1)}$ respectively.
4. Service of an item in the push system results in transition of states from $(x, y, 0)$ to $(x, y, 1)$ with probability $P_{(x,y,0);(x,y,1)}$. However, depending on the number of repeated attempts, the service of an item in the pull system can result in transition of states from $(x, y, 1)$ to $(x-1, y, 0)$, $(x-1, y-1, 0)$, \dots , $(x-1, 0, 0)$ with probabilities $P_{(x,y,1);(x-1,y,0)}$, $P_{(x,y,1);(x-1,y-1,0)}$, \dots , $P_{(x,y,1);(x-1,0,0)}$ respectively. When

the pull system contains only a single element, the service of an item results in transition from $(1, y, 1)$ to $(0, 0, 0)$ with probability $P_{(1,y,1);(0,0,0)}$.

For example, referring to the states $(2, 0, 0)$ (push with 2 items) and $(2, 0, 1)$ (pull with 2 items) in Figure 6.4, the arrival of a new pull-item with arrival rate λ in the system, leads to the transition into state $(3, 0, 0)$ and $(3, 0, 1)$ with probability $P_{(2,0,0);(3,0,0)}$ and $P_{(2,0,0);(3,0,1)}$ respectively. Similarly, arrival of a repeat-attempt item at these two states with an arrival rate $2\xi\lambda$ results in transition into the state $(2, 1, 0)$ and $(2, 1, 1)$ with probability $P_{(2,0,0);(2,1,0)}$ and $P_{(2,0,1);(2,1,1)}$ respectively. We have assumed strictly reciprocal service of a push and pull item. The average service rate of the push system is assumed to be μ' . Such a service of an item from the push system, indicates that the next service will be from the pull system. Referring to the same state, i.e., $(2, 0, 0)$ in Figure 6.4, the service of the item results in transition from state $(2, 0, 0)$ to state $(2, 0, 1)$ with probability $P_{(2,0,0);(2,0,1)}$ and service rate μ' . However, the service of an item results in different possibilities, because the item currently getting serviced might be present or absent in the repeat-attempt queue. If it is present in the repeat-attempt queue, then the number of entries of that particular item in the repeat-attempt queue also needs to be cleared. Hence, service from state $(2, 1, 1)$ results in transition to either of the states $(1, 0, 0)$ or $(1, 1, 0)$ with probabilities $P_{(2,1,1);(1,0,0)}$ and $P_{(2,1,1);(1,1,0)}$ with service rates μ_1 and μ_2 respectively.

In order to get the estimates of these probabilities (P), first we need to derive the probabilities of selecting a particular item for service from the pull-queue and repeat-attempt queue. Subsequently, we need to obtain the relations between different service rates and measure for transition probabilities of the Markov Chain. We first proceed to find out the selection probabilities of different data items in the pull and Repeat Attempt queue.

Since, there are x number of items currently present in the pull system, the actual items could be any combination of x elements chosen from total m data items in the system. Obviously, there are $\kappa = \binom{m}{x}$ number of combinations possible. We denote the combination by $\vec{C} = \{\vec{C}_1, \vec{C}_2, \dots, \vec{C}_\kappa\}$, where every \vec{C}_j is a x -element vector. Every element of this vector is a data item. We can select an element i from any of these vectors in $\binom{x}{1}$ ways. Now, once we have chosen i from a particular vector every other item of the remaining $x - 1$ items can be chosen from any element of the available vectors. It should be noted that same items can not be repeated, as repeated items reside in the *repeat-attempt queue*. In other words, any item selected can not be re-selected again. Hence, if p_i represents the access probability of item i , then probability $Pr[i]_Q$ of choosing any item i from the pull queue (without repetition) is given by the relation:

$$Pr[i]_Q = \binom{x}{1} \left[p_i \sum_{j_1=1, j_1 \neq i}^x p_{j_1} \dots \sum_{j_\kappa=1, j_\kappa \neq i, j_\kappa \neq j_z, \forall z < \kappa}^x p_{j_\kappa} \right] \quad (6.1)$$

However, it should be noted that since the pull queue does not contain the repeated instances of the items, the sum of total probability of the queue is less than 1. Hence all such probabilities $Pr[i]_Q$ need to be normalized. Hence the normalized probability is now given by:

$$Pr[i]_{norm} = \frac{Pr[i]_Q}{\sum_{j=1}^{\kappa} Pr[\vec{C}_j]} \quad (6.2)$$

where $Pr[\vec{C}_j]$ represents the probability of all the items belonging to the vector \vec{C}_j .

We now investigate into the Repeat-Attempt queue, where the elements can be repeated. They can be repeated once, twice or up to a maximum of m -times. We are looking to obtain the probability of this repetition

of elements. Proceeding in the similar approach as in Equation (6.1), we can obtain the probability of a particular item i to be repeated any number of times in the Repeat-Attempt queue. Let, $(Pr[i]_{Repeat})_y$ denotes the probability that the item i is repeated y times in the Repeat-Attempt queue. Now, for the first time, the item i can still be selected in $\binom{x}{1} = x$ different ways. However, since i will be repeated once more, after choosing it for once, it can still be selected in x ways for the second time and thereafter. The other terms for the remaining items can be chosen from any element of the available vectors. The restriction that the item can not be repeated (as in the pull queue) no longer exists in this repeat-attempt queue. Hence, proceeding in a similar way, the probability $(Pr[i]_{Repeat})_y$ that there are y number of repetition of the item i is given by the equation:

$$(Pr[i]_{Repeat})_y = \left[\sum_{j_1=1}^x \cdots \sum_{j_y=1, j_y \neq i}^x \cdots \sum_{j_\kappa=1, j_\kappa \neq i}^x p_{j_1} \cdots p_{j_y} \cdots p_{j_\kappa} \right] \times x^y p_i, \quad (\forall y, 1 \leq y \leq m) \quad (6.3)$$

The normalized probabilities of repeat-attempt states are now obtained by dividing the probability $(Pr[i]_{Repeat})_y$ by the total probability of all the elements in the repeat-attempt queue:

$$(Pr[i]_{Repeat})_{y_{norm}} = \frac{(Pr[i]_{Repeat})_y}{\sum_{i=1}^x \sum_{j=1}^y (Pr[i]_{Repeat})_j} \quad (6.4)$$

It should be noted that when a departure occurs from a repeat-attempt state, the next state always depends on the probabilities of the number of repeated attempts occurred. Let, μ and μ' be the overall service rate associated with the pull and push system. Also, let $\mu_0, \mu_1, \dots, \mu_y$ represents the fraction of overall pull service rate (μ) associated with $0, 1, \dots, y$ number of repetitions. Now each of this fractional service rate is responsible for servicing the particular item from the pull-queue and the corresponding

items repeated in the repeat-attempt queue. Hence, the fractional service rate can be estimated by multiplying the probability of item-selection from the pull queue and from the repeat-attempt queue. Thus, we have:

$$\begin{aligned}
\mu_y &= Pr[i]_{norm} (Pr[i]_{Repeat})_{y_{norm}} \mu, \\
\mu_0 &= (Pr[i]_{norm} [1 - \zeta]) \mu, \text{ where} \\
\zeta &= (Pr[i]_{Repeat})_{1_{norm}} + \dots + (Pr[i]_{Repeat})_{y_{norm}} \quad (6.5)
\end{aligned}$$

We are now in a position to compute the transitional probabilities in the Markov Chain. The transitional probabilities between any two states are estimated as the ratio of the transition rate between the initial and the final state with the total transition rate from the initial state. Hence, the expression for different transitional probabilities of the Markov Chain is now given as:

$$\begin{aligned}
P_{(x,y,0);(x+1,y,0)} &= \frac{\lambda}{\lambda + x\xi\lambda + \mu'} \\
P_{(x,y,0);(x,y+1,0)} &= \frac{x\xi\lambda}{\lambda + x\xi\lambda + \mu'} \\
P_{(x,y,0);(x,y,1)} &= \frac{\mu'}{\lambda + x\xi\lambda + \mu'} \\
P_{(x,y,1);(x+1,y,1)} &= \frac{\lambda}{\lambda + x\xi\lambda + \sum_{i=0}^y \mu_i} \\
P_{(x,y,1);(x,y+1,1)} &= \frac{x\xi\lambda}{\lambda + x\xi\lambda + \sum_{i=0}^y \mu_i} \\
P_{(1,y,1);(0,0,0)} &= \frac{\mu_0}{\lambda + x\xi\lambda + \mu_0} \\
P_{(x,y,1);(x-1,y,0)} &= \frac{\mu_0}{\lambda + x\xi\lambda + \mu_0} \\
P_{(x,y,1);(x-1,y-1,0)} &= \frac{\mu_1}{\lambda + xk\xi\lambda + \mu_0} \\
(\forall x \geq 1, \forall y \geq 0) & \\
&\dots\dots\dots \\
P_{(x,y,1);(x-1,0,0)} &= \frac{\mu_y}{\lambda + x\xi\lambda + \mu_0} \quad (6.6)
\end{aligned}$$

The transitional probabilities of the Markov Chain obtained in this manner now forms the transitional matrix, containing the necessary information of the hybrid system. Any entry corresponding to $(x, y, z), (x', y', z')$ in the transition matrix, actually contains the state transition probability $P_{(x,y,z);(x',y',z')}$ from (x, y, z) to (x', y', z') . Representing all the steady states by the vector $\vec{\pi}$ and the transition matrix by \mathbf{P} , an approximate measure of the steady state probabilities can be obtained by solving the following matrix equations associated with the Markov Chain:

$$\begin{aligned}\vec{\pi} &= \vec{\pi}\mathbf{P} \\ \vec{\pi}\mathbf{e} &= 1,\end{aligned}\tag{6.7}$$

where \mathbf{e} is a unit column vector. Solving the above equations helps us in obtaining the state probabilities $\pi = \{\pi(0, 0, 0), \dots, \pi(x, y, z)\}$. The average number of items in the system and the average waiting time is now estimated as:

$$\begin{aligned}E[Items] &= \sum_{x=0}^{D-K} \sum_{y=0}^x [\pi(x, y, 0) + \pi(x, y, 1)] \\ E[W] &= E[Items]/\lambda.\end{aligned}\tag{6.8}$$

This provides an average behavior of our newly proposed hybrid scheduling system, which considers repeated-attempts from the clients.

6.3 Simulation Experiments

In this section we validate the performance of our hybrid system through simulation experiments. The primary goal of hybrid scheduling is to reduce the expected access time. Before presenting the details of simulation results, we enumerate the salient assumptions and parameters used in our simulation.

1. The simulation experiments are evaluated for a total number of $D = 1000$ data items.
2. The overall arrival rate λ is varied between 5–20 arrivals per unit time. The value of μ and μ' is estimated as: $\mu = \sum_{i=1}^K (P_i \times L_i)$ and $\mu = \sum_{i=K+1}^D (P_i \times L_i)$ where P_i and L_i are the access probability and length of data item i , respectively.
3. The length of the data items are varied from 1 to 4.
4. In order to keep the access probabilities of the items from similar to very skewed, θ is dynamically varied from 0.20 to 1.40.
5. To compare the performance of our hybrid scheduling strategy with client's impatience, we have chosen the work in [32], as according to our knowledge, this is the only existing broadcast scheme which considered client's impatience.

In the following, we discuss a series of simulation results to demonstrate the efficiency of our two hybrid scheduling strategies.

Figure 6.5 demonstrate the variation of the expected access-time with different values of K and θ , for $\lambda = 10$, in our hybrid repeat-attempt scheduling system. With increasing values of cutoff point K , the expected access time initially decreases, attains a minimum value and then starts increasing again. This minimum point also provides the optimum cut-off point for which the framework gets an exact balance between the push and pull systems. Figure 6.6 shows the results of performance comparison, in terms of expected access time (in seconds), between our newly proposed repeat-attempt hybrid framework with the existing hybrid scheme due to Oh, et al. [32]. The effective combination of PFS and Stretch-optimal scheduling strategies, together with the repeat-attempt functionality results in the reduced waiting time in our hybrid scheduling framework.

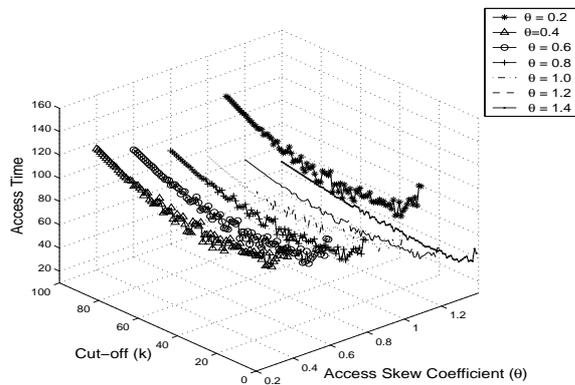


Figure 6.5: Performance of Hybrid Scheduling

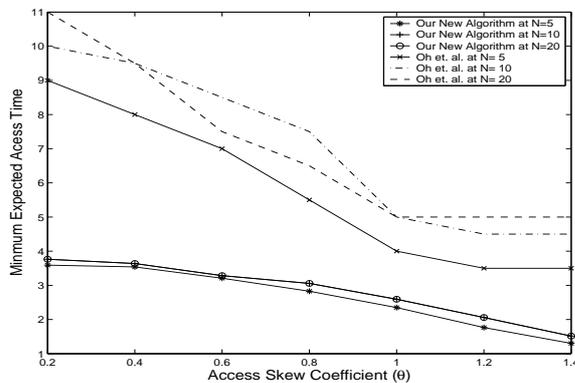


Figure 6.6: Performance Comparison with [32]

Figure 6.7 depicts the comparative view of the analytical results with the simulation results of our repeat-attempt hybrid scheduling framework. For the analytical results, we have numerically solved the Markov Chain in Figure 6.4 and the Equations 6.1– 6.8 to get an estimate of the average system performance. The analytical results closely match with the simulation results for expected access time with almost $\sim 95\%$ accuracy, thereby pointing out that the performance analysis is capable of capturing the average system behavior with good accuracy.

Figure 6.8 demonstrates that K lies in the range of 40–60 for three different arrival rates $\lambda = [5, 10, 20]$. Intuitively, this points out that the system

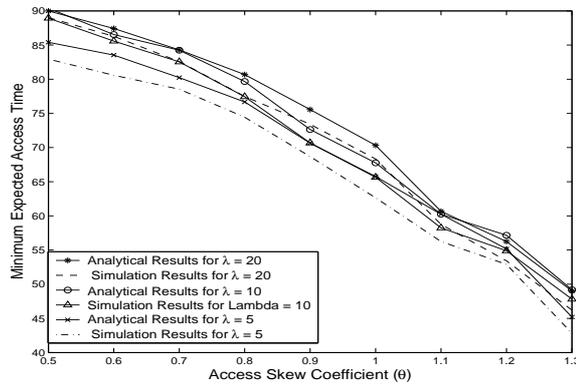


Figure 6.7: Simulation Vs Analytical Results

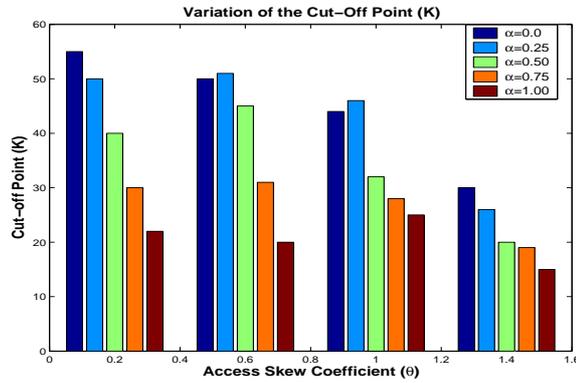


Figure 6.8: Variation of Cutoff-point (K)

has achieved a fair balance between push and pull systems to achieve the minimum expected access time.

6.4 Summary

In this chapter we have enhanced our hybrid scheduling to incorporate the client's repeat-attempt (retrial) behavior. The client's impatience often results in repeated attempts (retrials) for the same item. We have used suitable modeling, analysis and simulation experiments to capture the clients' retrials.

Chapter 7

Service Classification in Hybrid Scheduling for Differentiated QoS

In this chapter we propose a new service classification strategy [38], [42] for hybrid broadcasting to support the differentiated QoS in wireless data networks. The major novelty of our work lies in separating the clients into different classes and introducing the concept of a new selection criteria, termed as *importance factor*, by combining the clients' priority and the *stretch* (i.e., *max-request min-service-time*) value. The item having the maximum importance factor is selected from the pull queue. The service providers now provide different service level agreements (SLA), by guaranteeing different levels of resource provisioning to each class of clients. The QoS (delay and blocking) guarantee for different class of clients now becomes different, with the clients having maximum importance factor achieving the highest level of QoS guarantee. The performance of our heterogeneous hybrid scheduler is analyzed using suitable priority queues to derive the expected waiting time. The bandwidth of the wireless channels is distributed among the client-classes to minimize the request-blocking of highest priority clients. The cut-off point, used to segregate the push and pull items is efficiently chosen such that the overall costs associated in the system gets minimized.

7.1 Hybrid Scheduling with Service Classification

We assume an environment with a single server serving multiple clients, thus imposing asymmetry. The server-database consists of a total D distinct items, out of which K items are pushed and the remaining $(D - K)$ items are pulled. All the items have variable lengths. The access probability P_i , of an item i is governed by the Zipf's distribution. Every client is also associated with certain priority. These priorities provides the influence and importance of the clients to the service providers. The push-based broadcasting ignores the clients' requests, and uses a *Flat* round-robin scheduling strategy for cyclic broadcasting of popular data items.

The pull-scheduling, on the other hand, is based on a linear combination of the number of clients' requests accumulated and priorities. It should be noted that items with pending requests for higher priority clients should be serviced faster than the items having requests from lower priority clients. However, this scheme might suffer from *un-fairness* to the lower priority clients and also does not consider the number of clients' requests. A data item, requested by many clients having lower importance, might remain in the pull queue for a long time. Eventually, all the pending requests for that item might be lost (blocked). Hence, a better option is to consider both the number of pending requests and the priorities of all clients requesting the particular data item. A close look into the system reveals that, the service time required to serve an item is dependent on the size of that item. The larger the length of an item the higher is its service time. We introduce a new scheduling strategy that combines *stretch optimal or max-request min-service-time first* schedule with the *priority scheduling* to select an item from the pull-queue. Formally if, \mathcal{S}_i represents the stretch associated with item i and \mathcal{Q}_i represents the total clients' priority associated with item i , then the item selected from the pull-queue is determined by the

following condition:

$$\gamma_i = \max [\alpha \mathcal{S}_i + (1 - \alpha) \mathcal{Q}_i], \quad (7.1)$$

where α is a fraction $0 \leq \alpha \leq 1$, which determines the relative weights between the priority and the stretch value. Clearly, $\alpha = 0$ and $\alpha = 1$ makes the schedule priority-scheduling and stretch-optimal scheduling respectively.

```

Procedure HYBRID SCHEDULING;
divide the clients among different service-classes;
distribute the total available bandwidth among service
classes such that every class is assigned to a bandwidth
proportional to the sum of its clients' priorities;
while true do
  begin
  consider the access/requests arriving;
  ignore the requests for push item;
  append the requests for the pull item in the
  pull-queue with its arrival time and importance-factor;
  take out an item from the push scheduling and broadcast it;
  if the pull-queue is not empty then
    extract the item having maximum importance-factor
    ( $\gamma_i$ ) from the pull-queue;
    if the required bandwidth for the item is
      greater than the available bandwidth for the
      corresponding service class then
        drop that item and the corresponding requests;
    else
      assign the required bandwidth of the item and
      update the available bandwidth;
      transmit that item;
      clear the number of pending requests for that item;
      free the amount of required bandwidth and update
      the amount of available bandwidth;
    end-if
  end-while

```

Figure 7.1: Service Classification in Hybrid Scheduling

When a client needs an item i , it requests the server for item i and waits until it listens for i on the channel. Note that the behavior of the client is independent of the fact that the requested item belongs to the push-set or the pull-set. Depending on the priorities, the server first classifies

the clients into different service classes. Similarly, the server assigns the total available bandwidth (\mathcal{B}) to different service classes in such a way that the bandwidth distribution is directly proportional to the sum of the clients' priorities belonging to the particular class. Formally we can say, if n_1, n_2, \dots, n_x represents the number of clients in each of the x service classes, ρ_j is the priority associated with any client j and $\mathcal{B}_1, \mathcal{B}_2, \dots, \mathcal{B}_x$ represents the bandwidth provisioning in every class, then we have:

$$\mathcal{B}_1 :: \mathcal{B}_2 :: \dots :: \mathcal{B}_x = \sum_{j=1}^{n_1} \rho_j :: \sum_{j=1}^{n_2} \rho_j :: \dots :: \sum_{j=1}^{n_x} \rho_j, \text{ where } \sum_{j=1}^x \mathcal{B}_j = \mathcal{B} \quad (7.2)$$

The server goes on accumulating the set of requests from the clients. The algorithm starts with a fixed cutoff-point which separates the push and pull set. For any item arrived, it first determines if the item belongs to the push or the pull set. If the request is for a push item, the server simply ignores the request as the item will be pushed according to the online Flat, round-robin algorithm. However, if the request is for a pull item, the server inserts it into the pull queue with the arrival time, and updates its stretch value and total priority of all the clients' requesting that item. After every push, if the pull queue is not empty, the server chooses the item having maximum importance factor (γ_i) from the pull-queue. The bandwidth required by the data item is assumed to follow Poisson's distribution. If the required bandwidth of the data item is less than the bandwidth available for the corresponding service class, then the data item and the corresponding requests are lost. Otherwise, the server assigns the required bandwidth and transmits the item. Once the transmission is complete, the pending requests for that item in the pull-queue is cleared and the bandwidth used is released to update the available bandwidth. Figure 7.1 provides the pseudo-code of the hybrid scheduling algorithm executing at the server-side. Periodically the algorithm is executed for different cutoff-points and obtains the optimal cutoff-point which minimizes the overall access time

(delay).

7.2 Delay and Blocking in Differentiated QoS

In this section we study the performance evaluation of our hybrid scheduler system by developing suitable models to analyze its behavior. The prime concern of this analysis is to obtain an estimate of the minimum expected waiting time (delay) of the hybrid system. Since, this waiting time is dependent on the cutoff point K , investigation into the delay dynamics with different values of K is necessary to get the optimal cutoff point. As explained before in Section 7.1, the selection criteria in the pull system is dependent on both the stretch-value associated with the item and the priority of the clients requesting that particular item. Hence, the performance analysis also needs to consider the clients priority along with the stretch-value associated with every data item. We divide the entire analysis into two parts. In the first part, we consider the system without any role of the client's priority and obtain the expression for average number of items present in the system. In the second part, we introduce the explicit role of priorities in determining the average system performance.

7.2.1 Average Number of Elements in the System

Assumptions: The arrival rate in the entire system is assumed to obey the Poisson's distribution with mean λ' . The service times of both the push and pull systems are exponentially distributed with mean μ_1 and μ_2 , respectively. Let C , D and K respectively represents maximum number of clients, total number of distinct data items and the cut-off point. The server pushes K items and clients pull the rest $(D - K)$ items. Thus, the arrival rate in the pull-system is given by: $\lambda = \sum_{i=K+1}^D \mathcal{P}_i \times \lambda'$, where \mathcal{P}_i denotes the access probability of item i . We have assumed that the access

probabilities P_i follow the *Zipf's distribution* with *access skew-coefficient* θ , such that $\mathcal{P}_i = \frac{(1/i)^\theta}{\sum_{j=1}^n (1/j)^\theta}$.

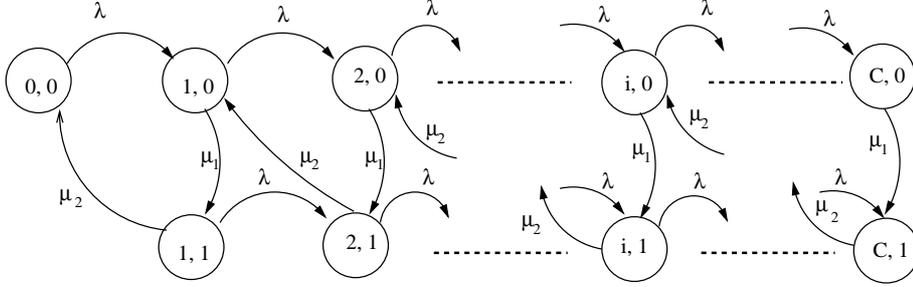


Figure 7.2: Performance Modeling of Our Hybrid System

Figure 7.2 illustrates the birth and death model of our system, where the arrival rate in the pull-system is given by λ . Any state of the overall system is represented by the tuple (i, j) , where i represents the number of items in the pull-system and $j = 0$ (or 1) respectively represents whether the push-system (or pull-system) is being served. The arrival of a data item in the pull-system, results in the transition from state (i, j) to state $(i + 1, j), \forall i \in [0, C]$ and $\forall j \in [0, 1]$. The service of an item in the push system results in transition of the system from state $(i, j = 0)$ to state $(i, j = 1), \forall i \in [0, C]$. On the other hand, the service of an item in the pull results in transition of the system from state $(i, j = 1)$ to the state $(i - 1, j = 0), \forall i \in [1, C]$. The details of steady-state flow balance equations and their solutions are explained in our previous work [35]. For the sake of clarity, we briefly highlight the major steps here. The steady-state behavior of the system (without considering priority) is represented by the equations given below:

$$p(0, 0) \lambda = p(1, 1) \mu_2$$

$$p(i, 0)(\lambda + \mu_1) = p(i - 1, 0)\lambda + p(i + 1, 1)\mu_2 \quad (7.3)$$

$$p(i, 1)(\lambda + \mu_2) = p(i, 0)\mu_1 + p(i - 1, 1)\lambda \quad (7.4)$$

where $p(i, j)$ represents the probability of state (i, j) . Dividing both sides of Equation (7.3) by μ_2 , letting $\rho = \frac{\lambda}{\mu_2}$, $f = \frac{\mu_1}{\mu_2}$, performing subsequent z -transform and using Equation (7.3), we get

$$P_2(z) = \rho p(0, 0) + z(\rho + f)[P_1(z) - p(0, 0)] - \rho z^2 P_1(z) \quad (7.5)$$

$$P_2(z) = \frac{f[P_1(z) - p(0, 0)]}{(1 + \rho - \rho z)} \quad (7.6)$$

Now, estimating the system behavior at the initial condition, we can state that the occupancy of pull and push states is given by: $P_2(1) = \sum_{i=1}^C p(i, 1) = \rho$ and $P_1(1) = \sum_{i=1}^C p(i, 0) = (1 - \rho)$. Using these two relations in Equation (7.5), we can obtain the idle probability, $p(0, 0)$ as: $p(0, 0) = 1 - \rho - \frac{\rho}{f}$. Differentiating both sides of Equation (7.5) with respect to z at $z = 1$, we estimate the expected number of elements in the pull-system ($E[\mathcal{L}_{pull}]$) as follows:

$$\left[\frac{\partial P_2(z)}{\partial z} \right]_{z=1} = E[\mathcal{L}_{pull}] = (\rho + f)\mathcal{N} + (1 - \rho) - (\rho + f) \times \left(1 - \rho - \frac{\rho}{f}\right) - \rho\mathcal{N} \quad (7.7)$$

where $\left[\frac{\partial P_1(z)}{\partial z} \right]_{z=1} = \mathcal{N}$ represents the average number of elements in the pull queue when a push request is being serviced.

7.2.2 Priority-based Service Classification

Every client j is associated with a certain priority q_j , which reveals the importance or class of that client. Obviously, this influences the arrival rate associated with every item. The arrival rate associated with i^{th} item for j^{th} priority-client is given by: $\lambda_i = \lambda p_i q_j$. Now, L_i and R_i represents the length and number of pending requests associated with the i^{th} item, then the stretch-value S_i associated with that item is given by the expression: $S_i = \frac{R_i}{L_i}$. If $E[\mathcal{L}_{pull}]$ represents the average length of the pull queue, then average number of i^{th} items present in the queue is given by $E[\mathcal{L}_{pull}]p_i$.

Hence, average importance of i^{th} item requested by j^{th} client is given by: $E[\mathcal{L}_{pull}] p_i q_j$. Representing the influence of the set of clients \mathcal{S} requesting for item i by $\mathcal{Q}_i = \sum_{j=1}^{\mathcal{S}} q_j$, the selection criteria of that element is now given by the following equation:

$$\varrho_i = \left(\alpha \frac{E[\mathcal{L}_{pull}] p_i}{L_i^2} + (1 - \alpha) E[\mathcal{L}_{pull}] p_i \mathcal{Q}_i \right) \quad (7.8)$$

It should be noted that the above equation actually resembles Equation 7.1. However, Equation 7.1 does not consider the number of i^{th} items present in the pull queue. Thus, Equation 7.8 actually generalizes Equation 7.1 and boils down to Equation 7.1, when $E[\mathcal{L}_{pull}] p_i = 1$. This condition provides the position of every item in the priority queue. In order to distinguish this measure with the client priority q_j , we term ϱ_i as the *importance-factor* of item i . We first analyze the system performance with clients belonging to two different classes [17], having two different importance factors. Subsequently, we extend the framework to incorporate clients having multiple importance factors.

Delay Estimation for Two Different Service Classes

Let, λ_1 and λ_2 represents the average arrival rate of the data items having importance factors 1 and 2, i.e., $\lambda = \lambda_1 + \lambda_2$. We also assume that the most important items have the right to get service before the second important item without *preemption*. Now, the probability of every state should incorporate the number of items belonging to both important factors and the class of item currently getting service. We denote it by $p(m, n, r, 1)$, such that: $p(m, n, r, 1) = Pr[m \text{ and } n \text{ units of importance factor 1 and 2 are present in the system and a unit of importance factor } r = 1(\text{or } 2) \text{ is in service, the system is in the pull mode}]$. Proceeding in a similar manner as shown in Section 7.2.1, we can obtain the steady state balanced equations

of the prioritized pull-system as:

$$\begin{aligned}
(\lambda_1 + \lambda_2 + \mu_2)p(m, n, 2, 1) &= \lambda_1 p(m-1, n, 2, 1) + \lambda_2 p(m, n-1, 2, 1) \\
(\lambda_1 + \lambda_2 + \mu_2)p(m, n, 1, 1) &= \lambda_1 p(m-1, n, 2, 1) + \lambda_2 p(m, n-1, 2, 1) \\
&\quad + \mu_2 [p(m+1, n, 1, 1) + p(m, n+1, 1, 1)] \\
(\lambda_1 + \lambda_2 + \mu_2)p(m, 1, 2, 1) &= \lambda_1 p(m-1, 1, 2, 1) \\
(\lambda_1 + \lambda_2 + \mu_2)p(1, n, 1, 1) &= \lambda_2 p(1, n-1, 1, 1) + \mu_2 [p(2, n, 1, 1) \\
&\quad + p(1, n+1, 2)] \\
(\lambda_1 + \lambda_2 + \mu_2)p(0, n, 2, 1) &= \lambda_2 p(0, n-1, 2, 1) + \mu_2 [p(1, n, 1, 1) + \\
&\quad p(0, n+1, 2, 1)] \\
(\lambda_1 + \lambda_2 + \mu_2)p(m, 0, 1, 1) &= \lambda_1 p(m-1, 0, 1, 1) + \mu_2 [p(m+1, 0, 1, 1) + \\
&\quad p(m, 1, 2, 1)] \\
(\lambda_1 + \lambda_2 + \mu_2)p(0, 1, 2, 1) &= \lambda_2 p(0, 0, 0, 1) + \mu_2 [p(1, 1, 1, 1) + p(0, 2, 2, 1)] \\
(\lambda_1 + \lambda_2 + \mu_2)p(1, 0, 1, 1) &= \lambda_1 p(0, 0, 0, 1) + \mu_2 [p(2, 0, 1, 1) + p(1, 1, 2, 1)] \\
(\lambda_1 + \lambda_2)p(0, 0, 0, 1) &= \mu_2 [p(1, 0, 1, 1) + p(0, 1, 2, 1)] \tag{7.9}
\end{aligned}$$

It should be noted that the probability of the idle state, i.e., $p(0, 0, 0, 0) = p(0, 0)$ remains same as before. The reason behind this is that the ordering of service does not affect the probability of idleness; i.e., $p(0, 0) = 1 - \rho - \frac{\rho}{f}$. Now, the occupancy of the pull states is ρ . Hence the fraction of time, the pull-system is busy with type-1 and type-2 items is given by: $\rho\lambda_1/\lambda$ and $\rho\lambda_2/\lambda$. Thus we have,

$$\sum_{m=1}^C \sum_{n=0}^C p(m, n, 1, 1) = \frac{\lambda_1}{\mu} \quad (a) \quad \sum_{m=0}^C \sum_{n=1}^C p(m, n, 2, 1) = \frac{\lambda_2}{\mu} \quad (b) \tag{7.10}$$

Obtaining a reasonable solution to these set of stationary equations is almost impossible. All we can do is to achieve an expected measure of the system performance. We perform two successive z-transforms over the Equations 7.10 (a)–(b), to get one and two dimensional z-transformed equations

in the following way:

$$P_{m1}(z) = \sum_{n=0}^{\infty} z^n p(m, n, 1, 1) \text{ and } P_{m2}(z) = \sum_{n=1}^{\infty} z^n p(m, n, 2, 1) \quad (7.11)$$

$$H_1(y, z) = \sum_{m=1}^{\infty} y^m P_{m1}(z) \text{ and } H_2(y, z) = \sum_{m=1}^{\infty} y^m P_{m2}(z) \quad (7.12)$$

Combining the above two-dimensional z-transforms we have:

$$\begin{aligned} H(y, z) &= H_1(y, z) + H_2(y, z) + p(0, 0, 0, 1) \\ &= \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} y^m z^n (p_{m,n,1,1} + p_{m,n,2,1}) + \sum_{m=1}^{\infty} z^m p(m, 0, 1, 1) \\ &\quad + \sum_{n=1}^{\infty} z^n p(0, n, 2, 1) + p(0, 0, 0, 1) \end{aligned} \quad (7.13)$$

Multiplying the set of steady-state equations by suitable powers of y and z and summing up accordingly we get,

$$\begin{aligned} \left(1 + \rho - \frac{\lambda_1 y}{\mu_2} - \frac{\lambda_2 z}{\mu_2} - \frac{1}{y}\right) H_1(y, z) &= \frac{H_2(y, z)}{z} + \frac{\lambda_1 y p(0, 0, 0, 1)}{\mu_2} - P_{11}(z) - \frac{P_{02}(z)}{z} \\ \left(1 + \rho - \frac{\lambda_1 y}{\mu_2} - \frac{\lambda_2 z}{\mu_2}\right) H_2(y, z) &= P_{11}(z) + \frac{P_{02}}{z} - p(0, 0, 0, 1) \left(\rho - \frac{\lambda_2 z}{\mu_2}\right) \\ P_{11}(z) &= \left(1 + \rho - \frac{\lambda_2 z}{\mu_2} - \frac{1}{z}\right) P_{02}(z) \\ &\quad + p(0, 0, 0, 1) \left(\rho - \frac{\lambda_2 z}{\mu_2}\right) \end{aligned} \quad (7.14)$$

Solution of the above three equations results in:

$$\begin{aligned} H(y, z) &= H_1(y, z) + H_2(y, z) + p(0, 0, 0, 1) \\ &= \frac{p(0, 0, 0, 1)(1 - y)}{1 - y - \rho y(1 - z - \lambda_1 y/\lambda + \lambda_1 z/\lambda)} \\ &\quad + \frac{(1 + \rho - \rho z + \lambda_1 z \mu_2)(z - y) P_{0,2}(z)}{z[1 + \rho - \lambda_1 y/\mu_2 - \lambda_2 z/\mu_2][1 - y - \rho y(1 - z - \lambda_1 y/\lambda + \lambda_1 z/\lambda)]} \end{aligned} \quad (7.15)$$

The above equation provides the final solution of the z-transforms associated with the two different priority classes of clients. This equation will

help us in obtaining the average performance of both the priority classes and also the overall expected system performance. As discussed earlier in the previous subsection, differentiating this equation will provide the average number of items present in the system. If L_1 and L_2 represents the average number of items for both the classes then,

$$L_1 = \left[\frac{\partial H(y, z)}{\partial y} \right]_{y=z=1} \quad \text{and} \quad L_2 = \left[\frac{\partial H(y, z)}{\partial z} \right]_{y=z=1} \quad (7.16)$$

The expected waiting time of the data items having two different importance factors now can be easily found by using the Little's formula as: $E[W_1] = L_1/\lambda_1$ and $E[W_2] = L_2/\lambda_2$.

Effect of Multiple Service Classes

The outline of the above procedure however fails to capture the expected system performance when number of importance-factors increase over 2. Thus a better way is to follow a *direct expected value approach* [17]. Considering a non-preemptive system with many importance-factors, let us assume the data items with importance-factor ρ_j have an arrival rate and service time of λ_j and μ_{2j} respectively. The occupancy arising due to this j^{th} data item is represented by $\rho_j = \frac{\lambda_j}{\mu_{2j}}$ ($1 \leq j \leq max$), where max represents maximum possible value of importance-factor. Also let σ_j represents the sum of all occupancy factors ρ_i , i.e., $\sigma_j = \sum_{i=1}^j \rho_i$. In the boundary conditions we have, $\sigma_0 = 0$ and $\sigma_{max} = \rho$. If we assume that a data item of importance-factor i arrives at time t_0 and gets serviced at time t_1 , then the wait is $t_1 - t_0$. Let at t_0 there are n_j data items present having priorities j . Also let, S_0 be the time required to finish the data item already in service, and S_j be the total time required to serve n_j . During the waiting time of any data item, n'_j new items having higher importance-factor can arrive and go to service before the current item. If S'_j be the total service time required to service all the n'_j items, then the expected waiting time for the

i^{th} item will be,

$$E[W_{pull}^{(i)}] = \sum_{j=1}^{i-1} E[S'_j] + \sum_{j=1}^i E[S_j] + E[S_0] \quad (7.17)$$

In order to get a reasonable estimate of $W_{pull}^{(i)}$, three components of Equation 7.17 needs to individually evaluated.

(i) *Estimating $E[S_0]$* : The random variable S_0 actually represents the remaining time of service, and achieves a value 0 for idle system. Thus, the computation of $E[S_0]$ is performed in the following way:

$$\begin{aligned} E[S_0] &= Pr[\text{Busy-System}] \cdot E[S_0 | \text{Busy-System}] \\ &= \rho \cdot \sum_{j=1}^{max} E[S_0 | \text{Serving an item having importance-factor} = j] \\ &\quad \times Pr[\text{item having importance-factor} = j] \\ &= \rho \times \sum_{j=1}^{max} \frac{\rho_j}{\rho \mu_{2j}} = \sum_{j=1}^{max} \frac{\rho_j}{\mu_{2j}} \end{aligned} \quad (7.18)$$

(ii) *Estimating $E[S_j]$* : The inherent independence of Poisson's process gives the flexibility to assume the service time $S_j^{(n)}$ of all n_j customers to be independent. Thus, an estimate of $E[S_j]$ can be obtained using the following steps:

$$E[S_j] = E[n_j S_j^{(n)}] = E[n_j] E[S_j^{(n)}] = \frac{E[n_j]}{\mu_{2j}} = \rho_j E[W_{pull}^{(j)}] \quad (7.19)$$

(iii) *Estimating $E[S'_j]$* : Proceeding in a similar way and assuming the uniform property of Poisson's,

$$E[S'_j] = \frac{E[n'_j]}{\mu_{2j}} = \rho_j E[W_{pull}^{(i)}] \quad (7.20)$$

The solution of Equation 7.17 can be achieved by combining the results of Equations 7.18–7.20 and using Cobham's iterative induction [17]. The

expected waiting time of the i^{th} item and the overall expected waiting time of the pull system is given as:

$$\begin{aligned}
E[W_{pull}^{(i)}] &= \frac{\sum_{j=1}^{max} \rho_j / \mu_{2j}}{(1 - \sigma_{i-1})(1 - \sigma_i)} \\
E[W_{pull}^q] &= \sum_{i=1}^{max} \frac{\lambda_i E[W_{pull}^{(i)}]}{\lambda}
\end{aligned} \tag{7.21}$$

The overall expected access time is obtained by combining the time taken to service the push and pull items. Since, the push set contains K items of heterogeneous lengths L_1, L_2, \dots, L_K , the average length of the push (broadcast) cycle is $\frac{1}{2} \sum_{i=1}^K L_i \mathcal{P}_i$. Thus, the expected access-time ($E[T_{hyb-acc}]$) of our hybrid system is now given by:

$$E[T_{hyb-acc}] = \frac{1}{2\mu_1} \sum_{i=1}^K L_i \mathcal{P}_i + E[W_{pull}^q] \sum_{i=k+1}^D \mathcal{P}_i, \tag{7.22}$$

where K is the cutoff-point used to segregate push and pull components of the hybrid system. It should be noted that one major objective of our proposed algorithm is to find out an optimal cutoff-point K such that this delay is minimized. The above expression provides an estimate of the average delay (waiting time) for different class of clients in our hybrid scheduling system. The service providers always try to reduce the delay of the high priority clients, in order to ensure their satisfaction. Apart from this delay, we would like get an estimate of the prioritized cost associated with each class of client. This cost is actually obtained as $q_j \times E[T_{hyb-acc}]$. Intuitively this cost provides an estimate of the client's influence on the service provider and the overall system.

7.2.3 Bandwidth Provisioning for Improved Blocking

As discussed earlier in Equation 7.2 in Section 7.1, the overall bandwidth B , of the wireless channels is distributed among the service classes in proportion to the total probabilities of the set of clients belonging to that

service class. The bandwidth required for transmission of any data item is assumed to follow Poisson's distribution with mean β . Thus the probability that the current bandwidth (b_{cur}) required is less than β is given by:

$$Pr[b < \beta] = \frac{\beta^\beta e^{-\beta}}{\beta!} \quad (7.23)$$

If the bandwidth availability (b_{avail}) is less than the current required bandwidth (b_{cur}) then the item is blocked and the corresponding requests are not satisfied, otherwise the item is transmitted and the bandwidth availability is updated. If we denote the successful transmission \mathcal{F} then we have,

$$\mathcal{F} = \begin{cases} 1, & b_{avail} \geq b_{cur} \\ 0, & otherwise \end{cases} \quad (7.24)$$

7.3 Simulation Experiments

In this section we validate the performance analysis of our prioritized hybrid system by performing simulation experiments. Since, the framework is made for differentiated services in wireless data networks, the primary objective is to reduce the cost associated in maintaining the different classes of clients, thereby reducing the loss that might incur from the churning of the clients. Naturally, the clients belonging to highest priority class should be provided with minimum possible waiting time, as the system suffers more in losing these highest priority clients. We first enumerate the set of assumptions used in our simulation. Subsequently, we provide the series of simulation results obtained.

7.3.1 Assumptions

1. The simulation experiments are evaluated for a total number of data items $D = 100$.

2. The overall average arrival rate λ' is assumed to be 5. The value of μ_1 and μ_2 is estimated as: $\mu_1 = \sum_{i=1}^K (\mathcal{P}_i \times L_i)$ and $\mu_2 = \sum_{i=K+1}^D (\mathcal{P}_i \times L_i)$.
3. The length of the data items are varied from 1 to 5, with an average of 2.
4. In order to keep the access probabilities of the items from similar to very skewed, θ is dynamically varied from 0.20 to 1.40. More specifically, we have assumed $\theta = \{0.20, 0.60, 1.0, 1.40\}$.
5. The entire set of clients is divided into three classes: *Class-A, having highest priority*, *Class-B with medium priority* and *Class-C with lowest priority*. The priorities are taken in the ratio 1 :: 2 :: 3. The fraction α associated in deriving the importance-factor is assumed to be in the range $[0, 1]$, where $\alpha = 1$ indicates the system ignoring the effect of priority and $\alpha = 0$ indicates the system ignoring the effect of stretch. The simulation experiments are performed for $\alpha = \{0, 0.25, 0.50, 0.75, 1.0\}$.
6. The distribution of clients among different classes is also assumed to obey Zipf's distribution, with lowest number of highest priority (Class-A) clients and highest number of lowest priority clients.
7. The overall average wireless channel bandwidth is assumed to be 64 Kbps. The average bandwidth requirement β is assumed to be 10 Kbps.
8. The cost associated in maintaining the three different classes of clients is assumed to be in proportion to the priority of the clients' classes. In other words the cost associated with Class-A, Class-B and Class-C clients are assumed to be in the ratio 3 :: 2 :: 1. As discussed earlier, this is used to obtain the prioritized cost (multiplication of client's priority and the expected delay) associated with different classes of clients.

7.3.2 Results with Two Client-Classes

Now we describe the set of simulation results obtained from our simulation experiments. First we concentrate on the simulation results with two different classes of clients. Subsequently we focus on the results having more service classes.

Overall Expected Delay

The goal of the first set of experiments is to investigate into the overall delay experienced by each class of clients. Figures 7.3–7.7 demonstrate the dynamics of total delay with the cut-off point experienced by two different classes of clients for $\alpha = \{0, 0.25, 0.50, 0.75, 1.0\}$ respectively. This is performed for different values of access skewness. The delay associated with the Class-A (highest priority) clients is very low (within 20 broadcast units). The delay experienced by the Class-B clients remains in the range 70–100 broadcast units. However, for both the classes of clients the delay is higher for low values of cut-off point (K). This is because for low values of K , the system deviates from the hybrid nature and can not achieve a good balance between push and pull set.

Prioritized Costs

The major objective of the second set of experiments is to look into the variation of the prioritized cost associated with each class of clients. As mentioned earlier, the system assigns the costs to each class of clients in proportion to the priority of that particular class. Figures 7.8–7.12 demonstrates the variation of prioritized costs with the cut-off point, associated with each class of clients for $\alpha = \{0, 0.25, 0.50, 0.75, 1.0\}$ and $\theta = 0.20, 0.60, 1.00, 1.40$. The overall objective is to pick up the particular value of cut-off point such that the total prioritized cost is minimized. Figure 7.13, on the other hand,

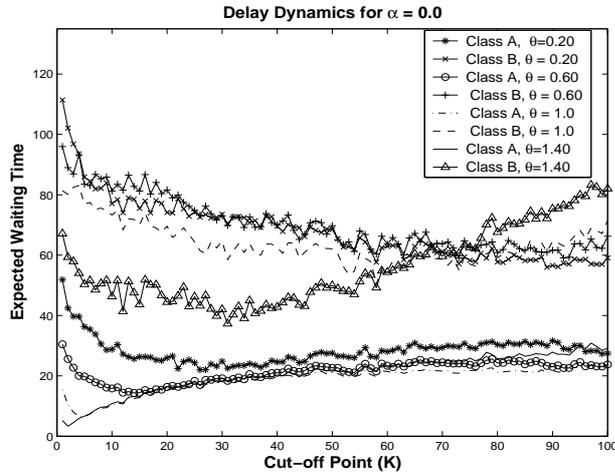


Figure 7.3: Delay Variation with $\alpha = 0.0$

shows the changes in total optimal prioritized cost of both the client-classes, with different values of α for $\theta = \{0.20, 0.60, 1.00, 1.40\}$. With increasing values of α the influence of priority increases and the prioritized cost reduces. The underlying reason is that for higher values of α the increased influence of priority results in serving the important clients first, thereby reducing the overall cost of the system.

Dynamics of Cutoff-Point

Figure 7.14 points out the changes in the cut-off point with different values of θ for all five values of α . For small values of θ the cut-off point lies in the range 40–50. This is because for small θ the items have similar probabilities and the system obtains a very good balance between the push and pull set. However, for higher values of θ the probabilities of the items get skewed. Thus, the size of the push-set (having high probabilities) shrinks, thereby resulting in low cut-off points (in the range 15–20).

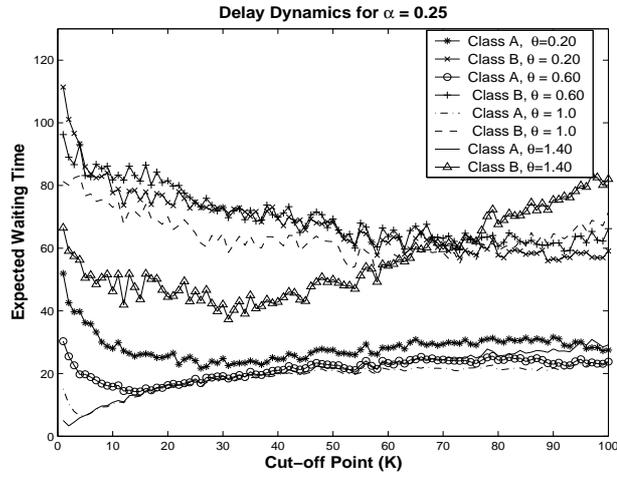


Figure 7.4: Delay Variation with $\alpha = 0.25$

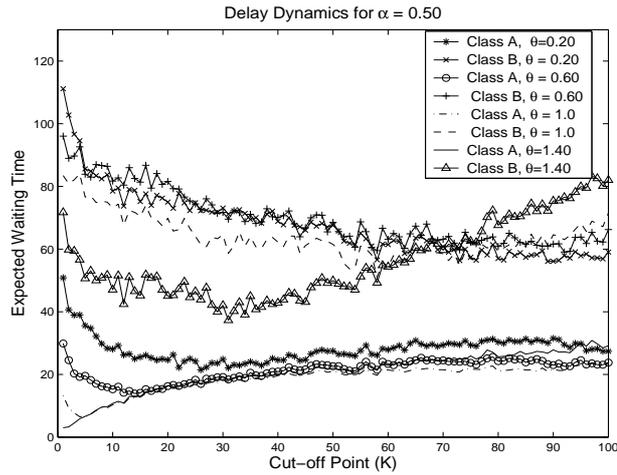


Figure 7.5: Delay Variation with $\alpha = 0.50$

Simulation and Analytical Results

Figure 7.15 demonstrates the comparison between analytical and simulation results for $\theta = 0.60$ and $\alpha = 0.75$. The analytical results are obtained using the Equation 7.22. We have chosen the values of α and θ so that these values are almost in the middle of their range. Analytical results closely match simulation results for both the set of clients, with a minor 10% de-

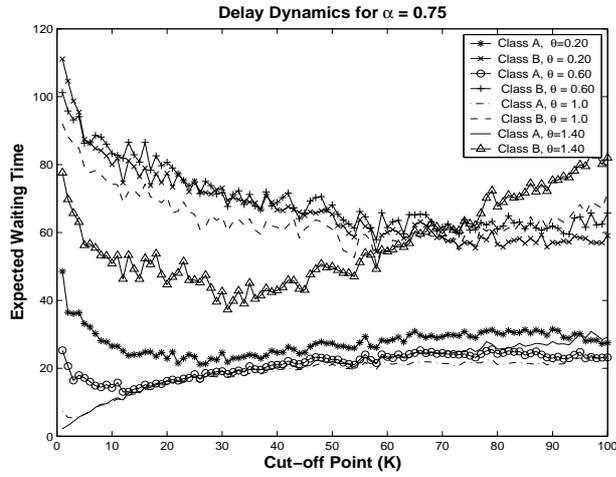


Figure 7.6: Delay Variation with $\alpha = 0.75$

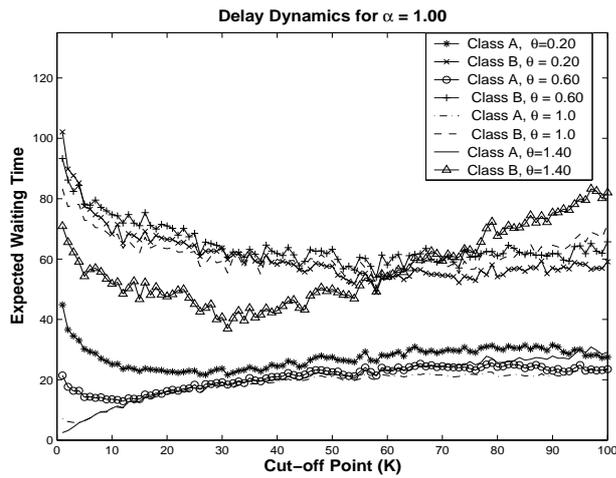


Figure 7.7: Delay Variation with $\alpha = 1.0$

viation. The minor deviation is attributed to the memoryless assumption in the system modeling.

7.3.3 Results with More Client-Classes

We now show the results with more than two different priority classes. While all our results are performed with three different priority classes,

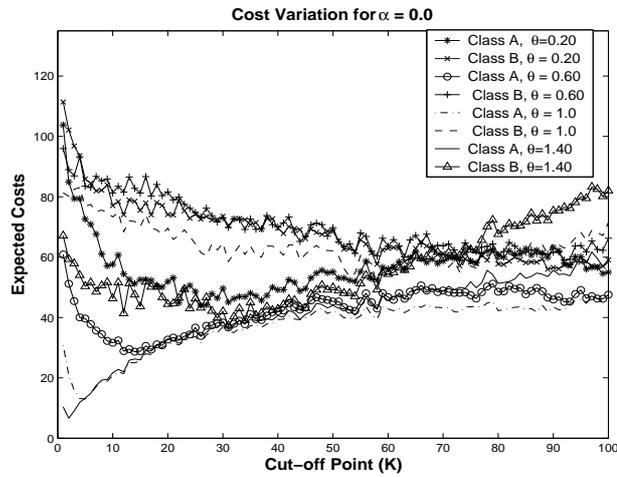


Figure 7.8: Cost Dynamics with $\alpha = 0.00$

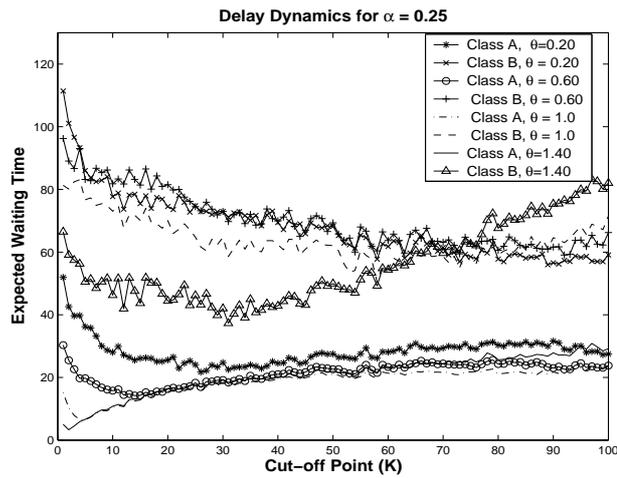


Figure 7.9: Cost Dynamics with $\alpha = 0.25$

more than three priority classes are just straight-forward extension of these results.

Overall Expected Delay

The goal of the first set of experiments is to investigate into the overall delay experienced by each class of clients. Figures 7.16–7.20 demonstrate the dynamics of total delay with the cut-off point experienced by three dif-

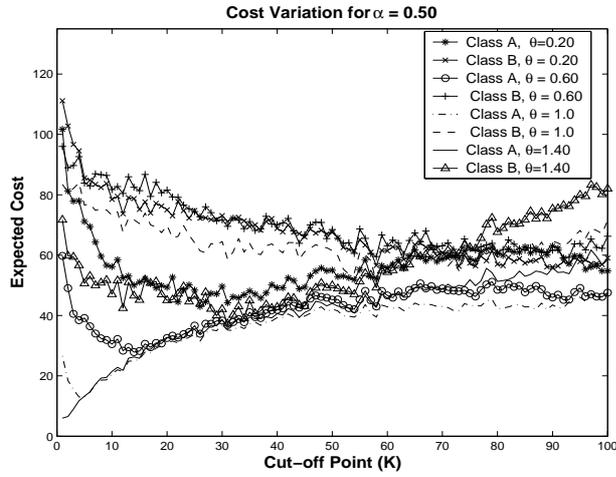


Figure 7.10: Cost Dynamics with $\alpha = 0.50$

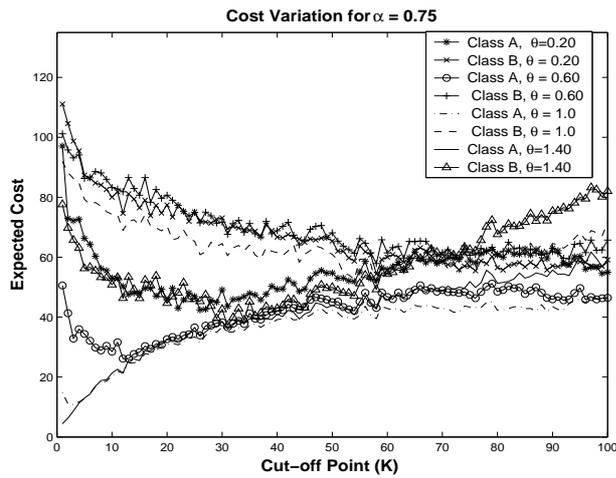


Figure 7.11: Cost Dynamics with $\alpha = 0.75$

ferent classes of clients for $\alpha = \{0, 0.25, 0.50, 0.75, 1.0\}$ respectively. This is performed for different values of access skewness. The delay associated with the Class-A (highest priority) clients is very low (within 5–10 broadcast units). The delay experienced by the Class-B clients remains in the range 20–40 broadcast units. The highest delay (40–70 broadcast units) is experienced by the Class-C clients. However, for all the classes of clients the delay is higher for low values of cut-off point (K). The reason is that

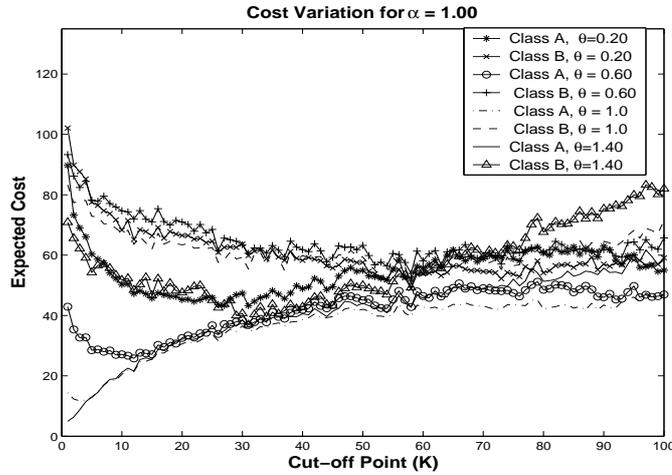


Figure 7.12: Cost Dynamics with $\alpha = 1.00$

for low values of K , the system deviates from the hybrid nature and can not achieve a good balance between push and pull set.

Prioritized Costs

The major objective of the second set of experiments is to look into the variation of the prioritized cost associated with each class of clients. As mentioned earlier, the system assigns the costs to each class of clients in proportion to the priority of that particular class. These costs are actually computed by multiplying the priority of the client-class with the expected delay. Figure 7.21 demonstrates the variation of prioritized costs with the cut-off point, associated with each class of clients for $\alpha = \{0.25, 0.75\}$ and $\theta = 0.60$. The overall objective is to pick up the particular value of cut-off point such that the total prioritized cost is minimized.

Figure 7.22, on the other hand, shows the changes in total optimal prioritized cost of all the client-classes, with different values of α for $\theta = \{0.20, 0.60, 1.40\}$. With decreasing values of α the influence of priority increases and the prioritized cost reduces. The underlying reason is that for lower values of α the increased influence of priority results in serving

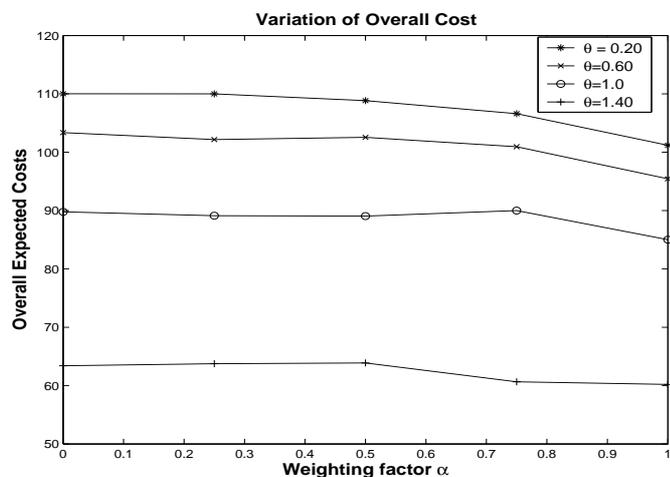


Figure 7.13: Variation of Overall Cost

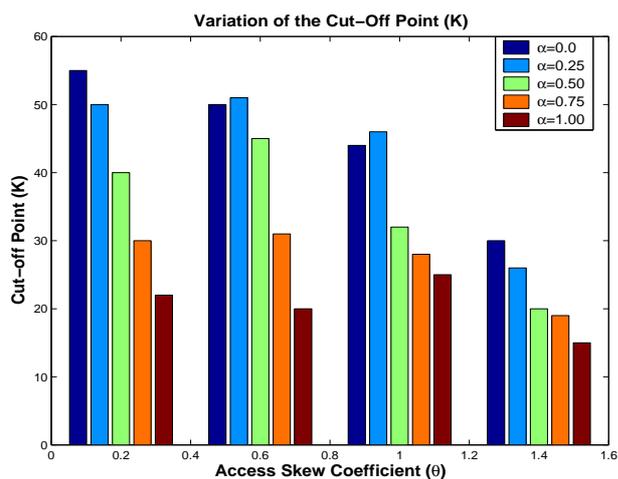


Figure 7.14: Variation of Cut-off Point

the important clients first, thereby reducing the overall cost of the system.

Differentiated Bandwidth Provisioning

One prime objective of this work is to point out the differentiated provisioning of wireless bandwidth among the different service classes. Figure 7.23 shows the percentage distribution of total available wireless bandwidth among the three different sets of clients. The class-A clients are assigned

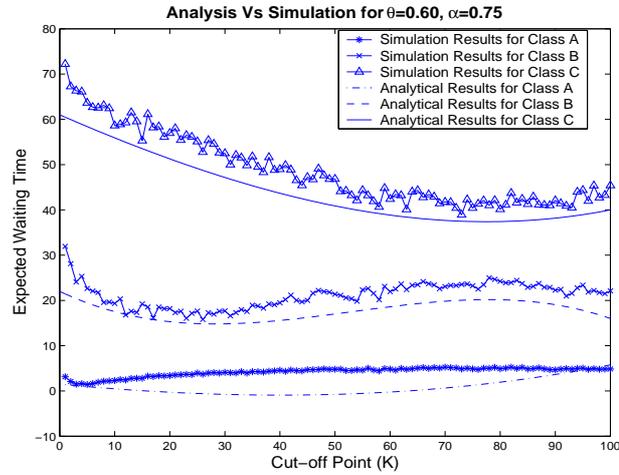


Figure 7.15: Analytical Vs Simulation Results

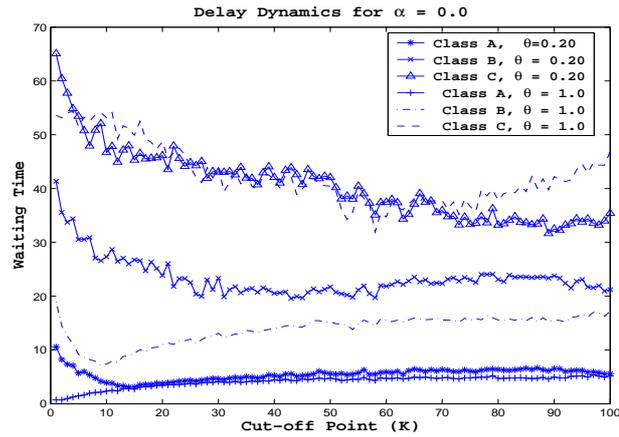


Figure 7.16: Delay Variation with $\alpha = 0.0$

with maximum fraction of bandwidth (almost 45%–50%), followed by class-B ($\sim 35\%$ – 40%). The class-C clients are provided with lowest bandwidth ($\sim 14\%$ – $\sim 20\%$).

This differentiated bandwidth provisioning helps in reduction of blocking for clients having higher priorities. Figure 7.24 points out that using such a differentiated bandwidth provisioning strategy the blocking of class-A and class-B clients can be reduced to $1/5$ of the original blocking (without

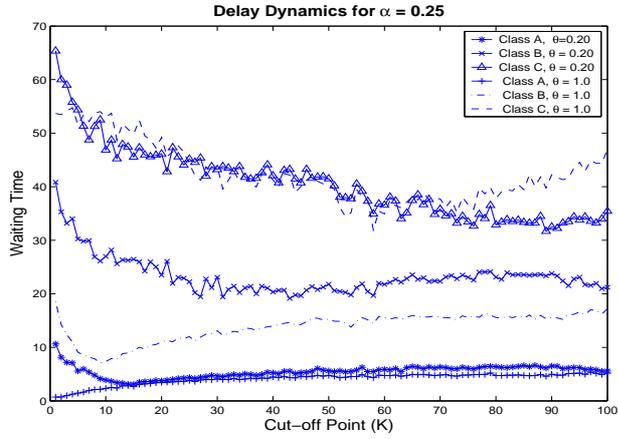


Figure 7.17: Delay Variation with $\alpha = 0.25$

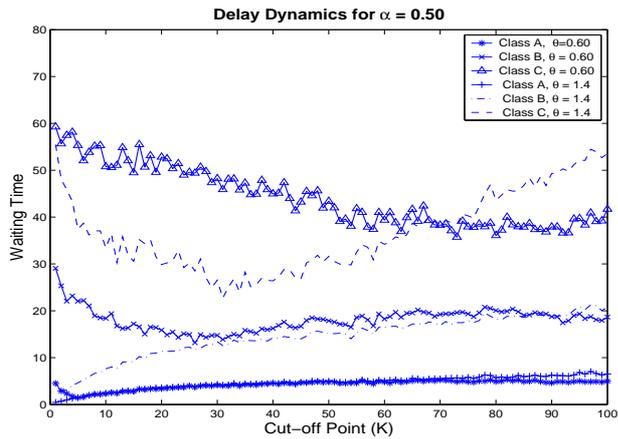


Figure 7.18: Delay Variation with $\alpha = 0.50$

any resource provisioning). However, the blocking of class-C clients are not reduced. The reason is that the improved service to class-A and class-B clients are provided at a minor expense of class-C clients. Since, class-A is the highest priority clients, such differentiated service provisioning results in increased of satisfaction to the higher priority clients, thereby reducing the overall churn rate and the cost of the service providers.

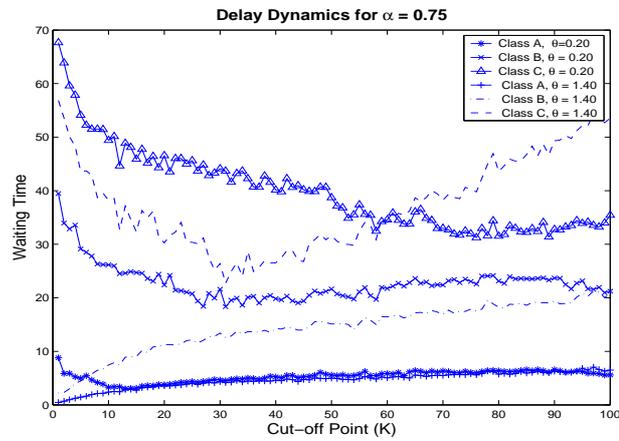


Figure 7.19: Delay Variation with $\alpha = 0.75$

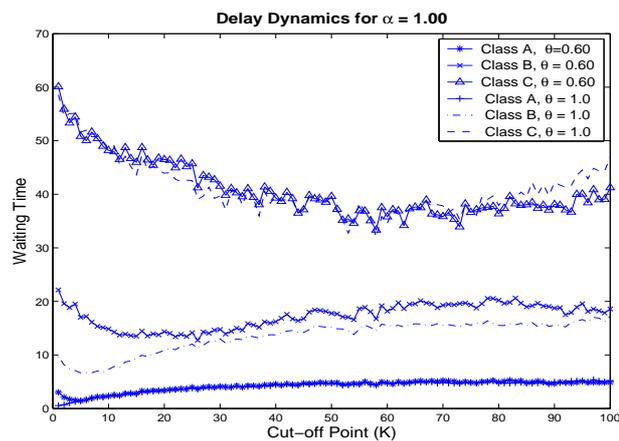


Figure 7.20: Delay Variation with $\alpha = 1.0$

Dynamics of Cutoff-Point

At this point of time, we want to look into the delay dynamics with the variation of the cutoff-point. As discussed earlier, the algorithm determines an optimal cutoff-point to reduce the overall delay. However, for different values of access-skewness (θ), the optimality of cutoff-point changes. Figure 7.25 points out these changes in the cut-off point with different values of θ for $\alpha = \{0, 0.75, 1.0\}$. For small values of θ the cut-off point lies in the range 40–55. This is because for small θ the items have similar proba-

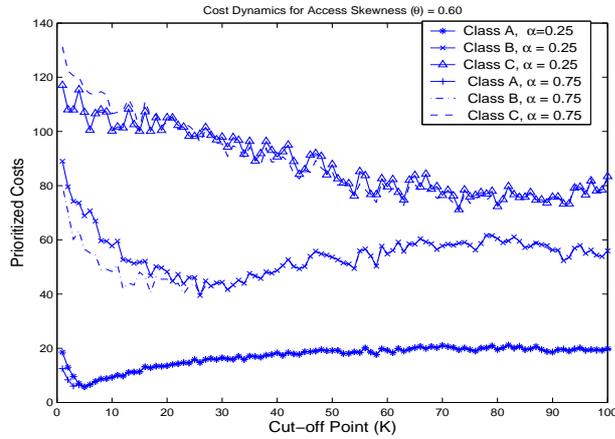


Figure 7.21: Cost Dynamics for Service Classes

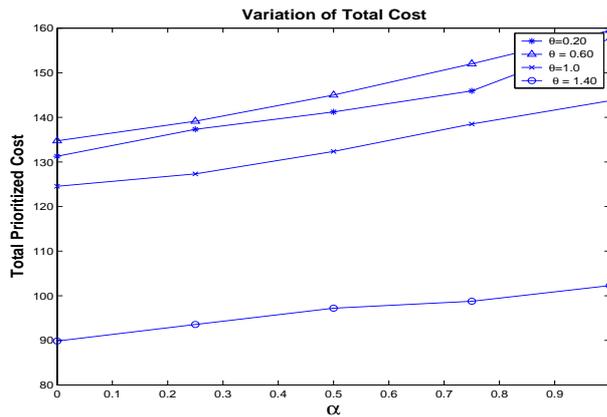


Figure 7.22: Variation of Prioritized Cost

bilities and the system obtains a very good balance between the push and pull set. However, for higher values of θ the probabilities of the items get skewed. Thus, the size of the push-set (having high probabilities) shrinks, thereby resulting in low cut-off points (in the range 15–20).

Simulation and Analytical Results

Figure 7.26 demonstrates the comparison between analytical and simulation results for $\theta = 0.60$ and $\alpha = 0.75$. The analytical results are obtained

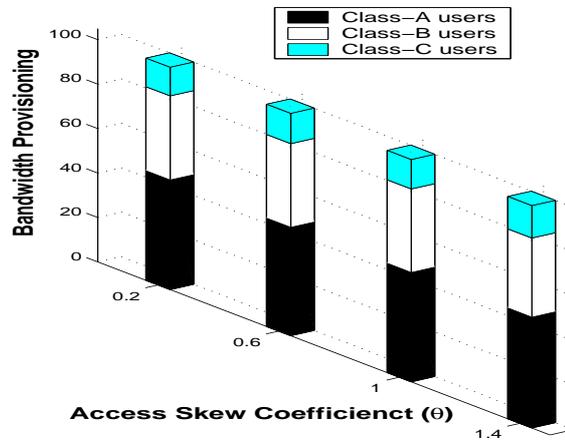


Figure 7.23: Bandwidth Provisioning

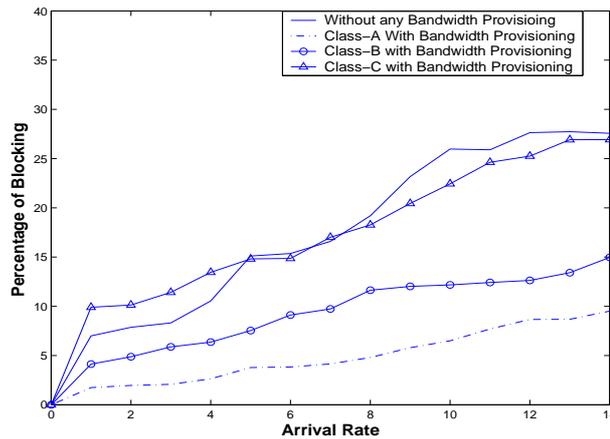


Figure 7.24: Reduction in Blocking

using the Equation 7.22. We have chosen the values of α and θ so that these values are almost in the middle of their range. Analytical results closely match simulation results for all the three set of clients, with a minor 10% deviation. The minor deviation is attributed to the memory-less assumption in the system modeling.

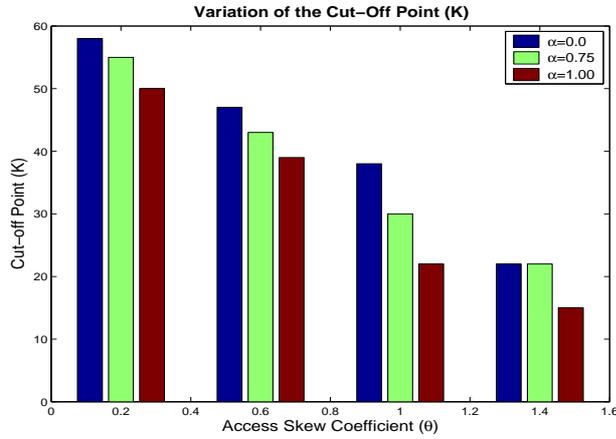


Figure 7.25: Variation of Cut-off Point

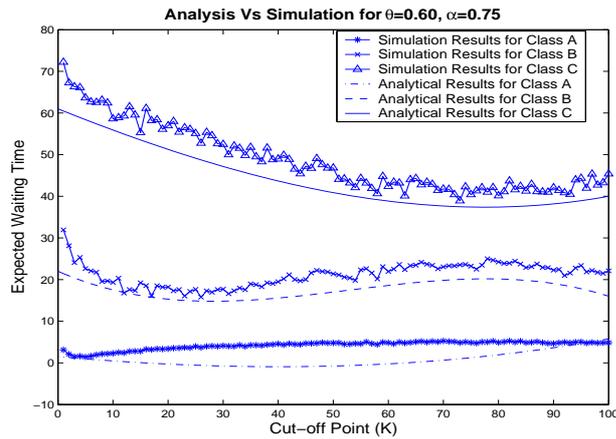


Figure 7.26: Analytical Vs. Simulation Results

7.4 Summary

In this chapter we have proposed a new priority based service classification scheme suitable for differentiated QoS. Subsequently, we have enhanced our hybrid scheduling strategy by using this service classification schemes. The scheme explores clients' priorities and items' popularity for differential distribution of wireless resources. This results in lower churning rate, improved QoS and more profit for the service providers.

Chapter 8

Online Hybrid Scheduling over Multiple Channels

In this chapter, a new on-line hybrid solution [40] for the Multiple Broadcast Problem is investigated. The new strategy first partitions the data items among multiple channels in a balanced way. Then, a hybrid push-pull schedule is adopted for each single channel. Clients may request desired data through the uplink and go to listen to the channel where the data will be transmitted. In each channel, the push and pull sets are served in an interleaved way: one unit of time is dedicated to an item belonging to the push set; and one to an item of the pull set, if there are pending client-requests not yet served. The push set is served according to a flat schedule, while the pull set according to the Most Request First policy. No complete knowledge is required in advance of the entire data set or of the demand probabilities, and the schedule is designed on-line.

8.1 Preliminaries: Definitions and Metrics

Let $D = \{1, 2, \dots, N\}$ be a set of N data items of unit length, and let each item i be characterized by a demand probability P_i . To start, consider a system with a single broadcast channel. A *broadcast schedule* S of any

period is an ordered sequence of data items selected from the set D . Note that if S is cyclic then the period is a positive integer, otherwise $period \rightarrow \infty$. Position t of S indicates the item of D that is broadcast at time $\tau \equiv t \pmod{period}$. The same item can be replicated in S . The *average spacing* between two consecutive instances of the same item i in S is termed s_i . Note that if i appears only once in S , then $s_i = period$. For total push systems, the *expected item delay* t_i for item i on S is defined as the average time a client waits before receiving i , assuming that, at any instant of time, clients start to listen with the same probability. Hence, $t_i = \frac{s_i}{2}$, for $1 \leq i \leq N$. Thus, the *Average Expected Delay* is given by:

$$AED(D) = \sum_{i=1}^N t_i P_i = \frac{1}{2} \sum_{i=1}^N s_i P_i \quad (8.1)$$

is the average over all items of D of their delay.

For the total pull systems, let $\delta_{i,r}$ be the actual delay between the request r for item i and the transmission time of item i . If R_i and $\#_i$ respectively denotes the set of requests for item i and its size, then the *average item delay* is defined as

$$\frac{\sum_{r \in R_i} \delta_{i,r}}{\#_i}$$

and the *Average Access Time*

$$AAT(D) = \sum_{i=1}^N \frac{\sum_{r \in R_i} \delta_{i,r}}{\#_i} P_i \quad (8.2)$$

is the average over all items of D of their average item delay.

For the hybrid push-pull systems, let $D = \Pi \cup \Delta$, where Π and Δ are the push and pull sets, respectively. Then, their performance is measured as the *Hybrid Time*, represented by:

$$HT(D) = AED(\Pi) + AAT(\Delta) \quad (8.3)$$

Finally, the Single Broadcast Problem is defined as the problem of finding the broadcast schedule S which minimizes Equations 8.1, 8.2, and 8.3 for push, pull and hybrid systems, respectively.

Note that, for total push schedules, particular assumptions lead to simplified formulations. For example, for a flat schedule F , since $s_i = N$ for $1 \leq i \leq N$ and $\sum_{i=1}^N P_i = 1$, it holds that

$$AED_F(D) = \frac{N}{2}$$

For a schedule generated by the Square Root Rule algorithm SRR , if the optimal spacing $s_i = \left(\sum_{j=1}^N \sqrt{p_j}\right) \sqrt{\frac{1}{P_i}}$ can be guaranteed, $AED_{SRR}(D) = \left(\sum_{j=1}^N \sqrt{p_j}\right)^2$. Since, in general, however, optimal spacing is not reachable because conflicts can arise on the same schedule position, the following weaker result holds [48]

$$AED_{SRR}(D) \geq \left(\sum_{j=1}^N \sqrt{p_j}\right)^2$$

Consider now a system with K broadcast channels. Clearly, a *multiple broadcast schedule* M consists of K single broadcast schedules, one per channel. For total push systems, the average delay t_i for item i is defined exactly as in the single channel environment, except that two item occurrences are considered consecutive if they happen to be close in the time, irrespective of on which channels they appear. Specifically, for a client listening simultaneously to the first j channels, two occurrences of i are consecutive and they are s_i apart if an occurrence of item i appears at time τ_i on channel j_1 , the subsequent earliest occurrence of i appears at time τ_{i+s_i} on channel j_2 , with $1 \leq j_1 \leq j_2 \leq j$, and no other occurrence appears in any other channel between 1 and j at the instants of time $\tau_{i+1}, \dots, \tau_{i+s_i-1}$. Now, let $AED^j(D)$ denote the AED experienced by a client listening to the first j channels. It is easy to see that a lower bound for $AED^j(D)$ is $\frac{AED(D)}{j}$. Note that, such a lower bound holds either when all data items are transmitted on each channel or when only a group of the data items is transmitted on each channel. Finally, the *Multiple Average Expected Delay* $MAED$ is defined as the AED averaged over all the subsets of channels

that clients can afford to read. To simplify, let clients listen only to consecutive subsets of channels, starting from channel 1. Thus, if a client listen to j channels, with $j > 1$, it will listen to channels $1, 2, \dots, j$. Denoting by π_j the probability that clients listen to j channels, and assuming that $\sum_{j=1}^K \pi_j = 1$,

$$MAED(D) = \sum_{j=1}^K AED^j(D)\pi_j \quad (8.4)$$

Clearly, $MAED = AED$ when $K = 1$.

As for AED, also simplified expressions of MAED hold. Namely, for the multiple schedule based on the Square Root Rule[48], we have,

$$MAED_{SRR}(D) \geq \sum_{j=1}^K \frac{\frac{1}{2} (\sum_{i=1}^N \sqrt{P_i})^2}{j} \pi_j \quad (8.5)$$

Moreover, MAED boils down to a much simpler expression when Skew allocation among channels and Flat schedules SF are assumed [53, 12]. Indeed, assume that the data items are assumed partitioned into K groups G_1, G_2, \dots, G_K , where the group G_j consists of the N_j data items transmitted by a flat schedule on channel j . Since each item is transmitted only by a channel, MAED is bounded by a constant only if clients listen to all channels. Hence, assuming $\pi_K = 1$ and $\pi_j = 0$, for any $1 \leq j \leq K - 1$, it is easy to see that, for any skewed allocation,

$$\begin{aligned} MAED_{\text{skew}}(D) &= AED^K(D) = AED_F(G_1) + \dots + AED_F(G_K) \\ &= \frac{1}{2} \sum_{j=1}^K \left(N_j \sum_{i \in G_j} P_i \right) \end{aligned} \quad (8.6)$$

Hence, the Allocation Problem, proposed in [53, 12], consists in finding the Skewed Allocation and Flat Schedule in such a way that Equation 8.6 is minimized. It is worthy to note at this point that such SF schedule, (denoted from now on as SF), can be found by a dynamic programming strategy in $O(NK \log N)$ time, as shown in [12].

Nonetheless, since the Allocation Problem is a special case of the Multiple Broadcast Problem, it is not known how far is the optimal MAED of the Allocation Problem from the optimal solution of the Multiple Broadcast Problem, even when it is considered restricted to the push systems. In conclusion, let us point out, that although *AAT* and *HT* performance measures can be generalized to the case of multiple channels, we are not aware of solutions already proposed in literature for the Multiple Broadcast problem for total pull or hybrid systems.

8.2 A New Multi-Channel Hybrid Scheduling

The above discussion suggests that many different schedules for the Multiple Broadcast Problem can be obtained by combining different data allocation strategies with different schedule strategies for single channels. The solution proposed in this paper for N data items and K channels combines a balanced allocation of data among channels with hybrid push-pull schedule per each single channel. The hybrid push-pull strategy guarantees that our solution adapts easily to changes of item demand-probability, while the balanced data allocation provides an easy way to incorporate new data items, without any data pre-processing. Moreover, since no more than $\lceil N/K \rceil$ items are assigned to each channel, by the flat schedule, MAED cannot go beyond $\lceil \frac{N}{2K} \rceil$. Finally, since each client knows in advance the channel on which the desired item will be transmitted, it can listen only to a channel per time.

First, the *Balanced K -channel allocation with Flat schedule*, briefly *BF*, solution is presented in Subsection 8.2.1. The performance of this simple solution is competitive with the *MAED* of both the *SRR* and *SF* schedules when all the items have almost the same demand probabilities. Then, in Subsection 8.2.2, the Flat schedule is substituted by the Hybrid schedule

to make our solution competitive even when the item demand probabilities are skewed.

8.2.1 Balanced K -Channel Allocation with Flat Broadcast Per Channel

```

Algorithm Balanced  $K$ -channel allocation :
begin
for  $i = 1, \dots, N$  do
 $j = ((i - 1) \bmod K) + 1$ ;
 $G_j = G_j \cup \{i\}$ 
end

```

Figure 8.1: The Balanced Allocation algorithm.

The balanced data allocation strategy, which assigns $O(N/K)$ items to each channel, lies in the opposite end of the skewed allocation strategy adopted for the K -Allocation Problem [53]. Specifically, consider a set of N data items $D = \{1, \dots, N\}$ and K channels, numbered from 1 to K . The items are partitioned in K groups G_1, \dots, G_K , where group $G_j = \{i | (i - 1) \bmod K = j - 1\}$, whose size

$$N_j = \begin{cases} \lceil \frac{N}{K} \rceil & \text{if } 1 \leq j \leq (N \bmod K), \\ \lfloor \frac{N}{K} \rfloor & \text{if } (N \bmod K) + 1 \leq j \leq K. \end{cases}$$

The Balanced Data Allocation algorithm is depicted in Figure 8.1. The items assigned to each channel are then broadcast locally by a flat schedule. Specifically, item i assigned to group G_j will be broadcast as the $\lceil i/K \rceil$ -th item of the flat schedule of channel j . Thus, the MAED of the BF schedule is given by the following relation:

$$MAED_{BF}(D) = \frac{1}{2} \sum_{j=1}^{N \bmod K} \left(\lceil \frac{N}{K} \rceil \sum_{i \in G_j} P_i \right) + \frac{1}{2} \sum_{j=N \bmod K + 1}^K \left(\lfloor \frac{N}{K} \rfloor \sum_{i \in G_j} P_i \right) \quad (8.7)$$

	$N; \theta$					
Algorithm	2500; 0	2500; 0.1	2500; 0.2	2500; 0.4	10; 0.8	500; 0.8
SRR	312.5	311.65	308.75	294.201	1.13	45.20
SF	312.5	311.86	309.69	298.44	1.17	47.53
BF	312.5	312.5	312.5	312.5	1.25	62.5

Table 8.1: The lower bound of the *MAED* for the *SRR*, *SF*, and *BF* Schedules.

It can be seen that $\lfloor \frac{N}{2K} \rfloor \leq MAED_{BF}(D) \leq \lceil \frac{N}{2K} \rceil$. *BF* is periodic and independent of the demand probabilities. Moreover, it is easy to see how the *BF* schedule can be updated when the size N of the set of data items increases by one. More specifically, the the new item $N + 1$ will become the $\lceil (N + 1)/K \rceil$ -th item of channel $j = (N \bmod K) + 1$.

Table 8.1 compares the performances of the *BF* schedule, the *SF* schedule, and the lower bound, of the performance of the *SRR* schedule, as given in Equation 8.5. The demand probabilities of the items are assumed to follow the Zipf distribution whose skew coefficient is θ ; i.e., $P_i = \frac{(1/i)^\theta}{\sum_{i=1}^N (1/i)^\theta}$, for $1 \leq i \leq N$. The parameters N and θ have been chosen to range, respectively, in $10 \leq N \leq 2500$ and $0 \leq \theta \leq 0.8$, while K is fixed to 4. The demand probabilities become skewed as θ approaches 1. Evaluated the distance in percentage between the *MAED* of the *BF* schedule and the *MAED* of the *SF* schedule as

$$\epsilon = \frac{MAED_{BF} - MAED_{SF}}{MAED_{SF}},$$

it is clear that the distance between the simple *BF* schedule is no larger than 4% for $\theta \leq 0.4$, leading to a very satisfying trade-off between efficiency and simplicity. However, the gap is marked for large values of θ . Our new hybrid scheduling per channel, proposed in the following section, improves in this respect.

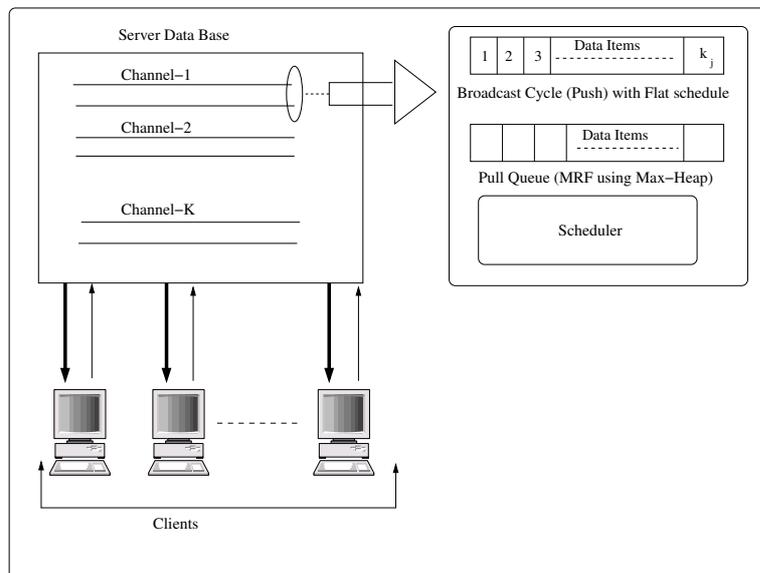


Figure 8.2: Multi-Channel Hybrid Scheduling Environment

8.2.2 On-Line Balanced K -Channel Allocation with Hybrid Broadcast Per Channel

In this section, we investigate into the improvement on the MAED of the BF -algorithm, while using the Balanced K -channel allocation to partition the data items among the channels, but by replacing the flat schedule with the following new hybrid schedule at each channel. Figure 8.2 explains this multi-channel, asymmetric, hybrid communication environment. For each channel j , the hybrid algorithm first partitions the group G_j assigned to each channel in two sets: the *push-set* Π_j , whose items $\{1, \dots, k_j\}$ will be broadcast according to a flat schedule and the *pull-set* Δ_j , whose items will be sent *on-demand*. The hybrid schedule alternates between the transmission of one item extracted from the push-set and the transmission of one item from the pull-set. At each pull turn, the item to be sent on demand is the item most requested so far by clients. Note that the push set may gain several consecutive turns if there are no pending requests for items of

the pull set.

The algorithm that runs at the client site is depicted in Figure 8.3. A client, desiring to receive item i , sends to the server an explicit request through the uplink if $i > k_j$. Then, it goes to listen to channel $j = (i - 1) \bmod K + 1$ to which item i has been assigned by the balanced allocation algorithm, and waits until i is transmitted.

```

Algorithm Client-Request (item  $i$ ):
/*  $i$  : the desired item */
begin
 $j = (i - 1) \bmod k + 1$ ;
if  $i > k_j$  then send to the server the
request for item  $i$ ;
wait on channel  $j$  until  $i$  is transmitted;
end

```

Figure 8.3: The Client-request Algorithm at the Client Side.

The algorithm at the server site is illustrated in Figure 8.4. For each channel j , the server stores in F_j the flat schedule of Π_j , whose current length is k_j . For each item i of the pull set, the server maintains the number $\#_i$ of requests received between two consecutive transmissions of that item in a max-heap H_j . The requests are checked before each push turn. Note that only items of the pull set can be requested. The item broadcast at the pull turn is the one stored in the heap root, that is the item that has received so far the largest number of requests. After the pull transmission of item i , $\#_i$ is always set to 0. Note that to decide the next item to be pushed costs constant time, while $O(\log \Delta_j)$ is required to maintain the heap after each delete-max operation. The new algorithm is on-line since it decides at run time the new item to be transmitted.

In order to have a schedule adaptive to noticeable changes of the demand probabilities, a mechanism for dynamically varying the push and pull sets is given based on the threshold σ . When item i is broadcast at the pull turn,

```

Algorithm Hybrid (channel  $j$ , pull set  $\Pi_j$ , push set  $\Delta_j$ );
while (true) do
begin
    check the requests received after the last check;
    for every item  $i$  that has been requested do
         $\#_i = \#_i + 1$ ;
        update  $H_j$ ;
    broadcast the current item of  $F_j$ ;
    update  $F_j$ ;
    if ( $H_j \neq \emptyset$ ) then
         $i = \text{root}(H_j)$ ;
        pull item  $i$ ;
        if  $\#_i > \sigma$  then move  $i$  from  $\Pi_j$  to  $\Delta_j$ ;
         $\#_i = 0$ ;
end;

```

Figure 8.4: The Hybrid Algorithm at the Server Side

if $\#_i > \sigma$, i is inserted in the push set as the last item of the flat schedule. Observe that although the push set initially consists of consecutive items, it may become fragmented. Then, the client needs more information to learn to which set the desired item belongs. More precisely, the server will supply the index of the changes occurred at the push sets, which is sent in a compressed form along with each single data, and periodically defragmentation policies are applied to globally renumber the data items.

It remains to discuss the *MAED* performance of the Balanced K -channel allocation with Hybrid schedule per channel, briefly *BH*, algorithm. As for the *BF* algorithm, the performance of *BH* is bounded by a constant only if the clients listen to all channels. Hence, $\pi_k = 1$ and $\pi_j = 0$ for $1 \leq j \leq k - 1$. Restricted to the push sets, *BH* reduces to a *BF* schedule. Recalling that clients must afford to listen to all channels,

its *MAED* performance measure is given by:

$$\begin{aligned}
MAED_{BH}(D) &= \gamma MAED_{SF}(\Pi_1 \cup \Pi_2 \cup \dots \cup \Pi_k) + \sum_{j=1}^K AAT(\Delta_j) = \\
\gamma \sum_{j=1}^K AED_F(\Pi_j) + \sum_{j=1}^K AAT(\Delta_j) &= \gamma \sum_{j=1}^K \sum_{i=1}^{k_j} \frac{k_j}{2} P_i + \sum_{j=1}^K \sum_{i=k_j+1}^{N_j} \frac{\sum_{r \in R_i} \delta_{r,i}}{\#i} P_i,
\end{aligned} \tag{8.8}$$

where γ is the *interleaving coefficient* and varies from 1, when only push turn occur, to 2, when every push turn is followed by a pull turn. When the push-sets are small, the time spent at the *BF* schedule becomes shorter, but the pull-sets are larger, leading to longer access time if the system is highly loaded. Thus, the two sets should be chosen in such a way that they reflect the load of the system to gain the advantages of both push and pull based schedules.

8.3 Simulation Results

In this section, simulation experiments are reported in order to discuss the performance of our multi-channel scheduling strategies. Before going into the details of simulation results, the major assumptions and parameters used for our experiments are summarized.

1. The simulation experiments are evaluated for a total number of data items $N = 2000$.
2. The request arrival time is assumed to obey Poisson distribution with mean $\lambda = 10$, which simulates a middle load of the system. The item requests follow the Zipf distribution, defined in Section 8.2.1. The average service time for every request is assumed to be 1.
3. The number of channels varies between 2–4.

- The demand probabilities follow the Zipf distribution with θ dynamically varied from 0.30 to 1.30.

Finally, observe that all the experiments involving *BH* and *SRR* schedules were executed 10 times, and the performance average has been reported.

8.3.1 Results

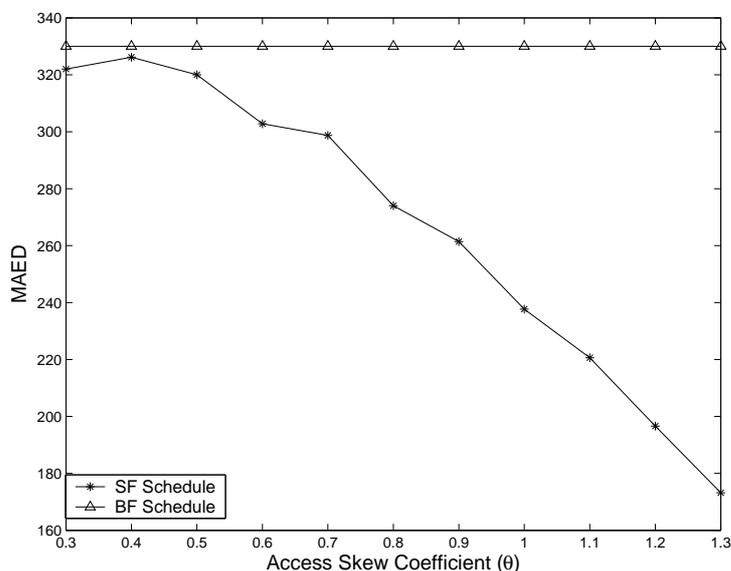


Figure 8.5: *MAED* Performances of the *BF* and *SF* Schedules

Figure 8.5 shows the performance of the *SF* and *BF* schedules for $N = 2000$, $K = 3$ and $0.3 \leq \theta \leq 1.3$. It should be noted that the results are independent of the arrival time of the requests, since two total push schedules are considered. Clearly, the *MAED* performance of the *BF* schedule is also independent from the demand probabilities, as shown in Equation 8.7. The *SF* schedule results in significant gains in overall expected access time for high values of θ . The major objective of our *BH* schedule is to reduce such a gap performance.

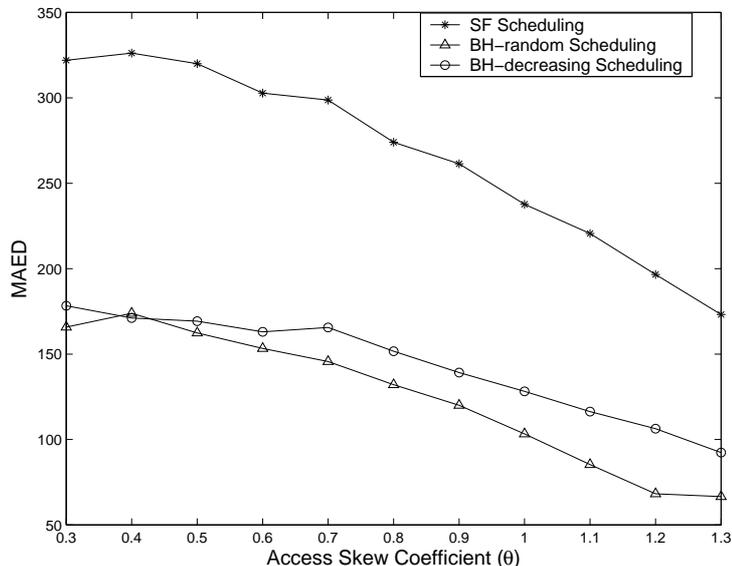


Figure 8.6: *MAED* Performances of the New Multi-channel Hybrid and the *SF* Schedule

Figure 8.6 demonstrates the performance efficiency of the *BH* schedule over the *SF* schedule. In addition to the *BH* schedule as described in Section 8.2.2, a variant that maintains in each channel the item of the push set sorted by decreasing demand probabilities is studied. Note that the ordering is local into each channel. In this way, the push set is initialized with hot items, and similarly the pull set with the cold items. So, from now on, let *BH-random* denote the basic hybrid schedule, while *BH-decreasing* the new variant. Both the *BH* schedules result in an improvement of almost half of the performance of the *SF* schedule.

Figure 8.7 shows the gain achieved by *BH* schedules on different numbers of channels, for $\theta = 0.50$ or $\theta = 1.00$. Even for different number of channels the *BH*-schedules achieve almost half of the *MAED* measure in comparison to the *SF*-schedule.

We have also taken a look into the distribution of items among different channels. While the Balanced Allocation distributes the items equally

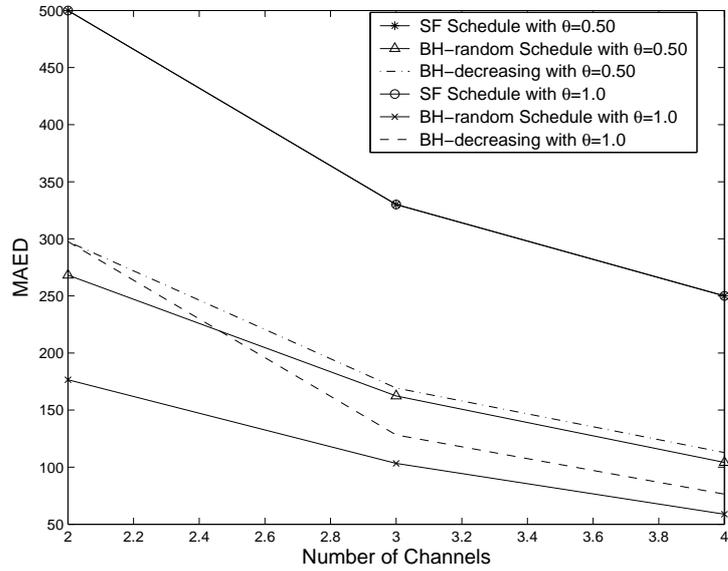


Figure 8.7: MAED Performances of the SF, BH-random and BH-decreasing Schedules

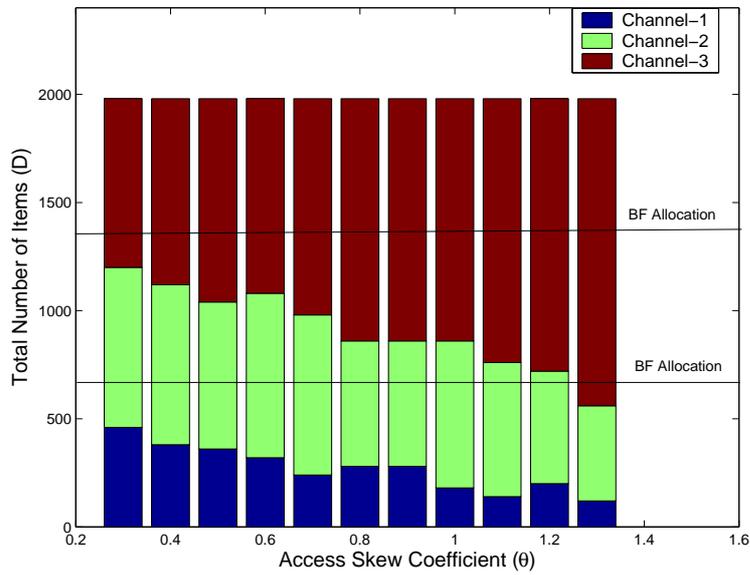


Figure 8.8: Size of the channel groups of the SF schedule when $K = 3$.

among the channels and the Skewed Allocation is twisted, different sizes of the push sets of the BH schedule can be selected initially. Figure 8.8

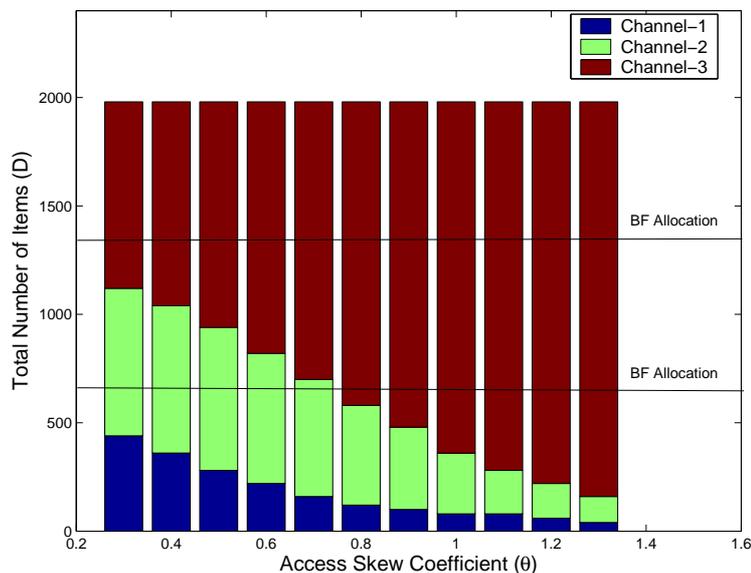


Figure 8.9: Size of the push sets of the BH schedule when $K = 3$.

and 8.9 show that, for a fixed value of the skew parameter θ of the Zipf distribution, and assuming all the push sets initially empty, when the BH schedule reaches a steady state (i.e., when the threshold mechanism does not move any items), the sizes of the push sets are skewed at least as much as that of the groups of the SF schedule when $\theta \leq 0.4$ and much more skewed for larger values of θ .

Finally, Figure 8.10 shows that both BH -random and BH -decreasing schedules outperform the SRR -schedule. Note that the SRR -schedule is determined on-line, but as for all push systems, it only knows the system load through the demand probabilities. So, for fixed θ , while BH reacts to the changes of the load of the system because it listens to the clients, SRR cannot.

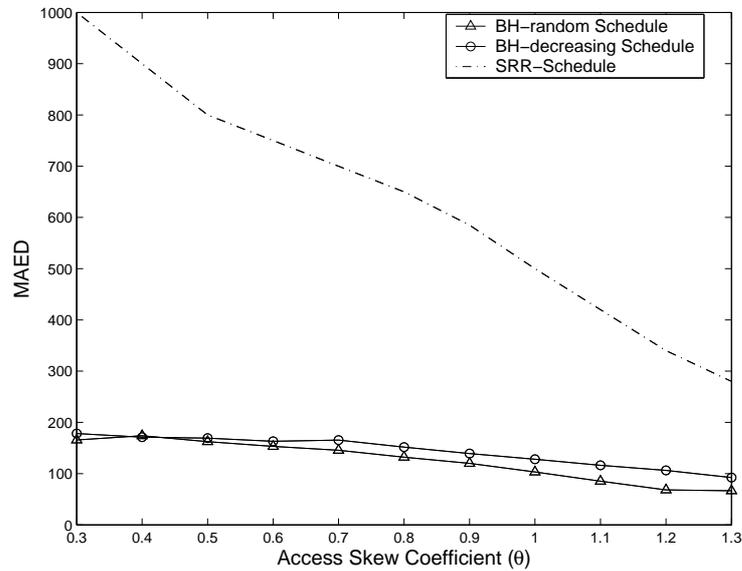


Figure 8.10: Performance Comparison of the *SRR* and *BH* schedules

8.4 Summary

In this chapter we have enhanced our hybrid scheduling strategy to span it over multiple channels. The data items are partitioned in an online, round-robin fashion over all the channels. Dynamic hybrid scheduling is then applied over every channel. The scheme significantly gains over the existing optimal skewed partition, followed by push scheduling in each channel.

Chapter 9

Conclusions and Future Research Issues

In this thesis we have developed a framework for hybrid scheduling in asymmetric wireless environments. The scheduling and data transmission strategies can be broadly classified into push and pull scheduling schemes. However, both of these push and pull scheduling strategies suffer from some specific disadvantages. Hence, a hybrid scheduling that explores the advantages of both push and pull scheduling appears to be more attractive. We first develop a basic hybrid scheduling scheme which combines the push and pull scheduling schemes independent of the *build-up point*, i.e., without restricting the pull-queue size to be 1. The hybrid scheduling system, designed by us uses push scheduling to broadcast the popular data items and takes the help of pull scheduling to transmit the less popular data items. The system computes the packet fair scheduling (PFS) for push system and accumulates the clients' request in the pull queue. The pull system works on most request first (MRF) scheduling. The system alternatively performs one push and one pull method. The cutoff point, which segregates between the push and pull scheduling is chosen in such a manner that the overall average access time experienced by the clients is minimized. This hybrid scheduling strategy is enhanced to incorporate heterogeneous data

items (i.e., items of variable lengths). While the basic of the push schedule remains un-changed, pull scheduling now needs to consider the item lengths also. The underlying reason is that items of variable lengths have different service times. This leads us to use the stretch-optimal scheduling principle to choose an item from the pull queue. Performance analysis and simulation results point out the efficiency of this heterogeneous hybrid scheduling scheme. While this scheduling strictly alternates between one push and one pull method, a better approach is to adapt the operations depending on the overall system load. Hence, we further improve the hybrid push-pull scheduling to introduce multiple consecutive push and pull operations depending on the overall load and dynamism of the system. A procedure for providing the performance guarantee of the system to meet the deadline specified by the clients is also developed.

A close look into the practical systems reveals that in most systems some clients might be impatient. This impatience of the clients significantly affects the performance of the system. An *impatient* client can leave the system even before the request is actually serviced. Excessive impatience might result in clients antipathy in joining the system again. On the other hand, an impatient client might send multiple requests for the same data item, thereby increasing the access probability of the item. This develops an anomalous picture of the system, as the server might consider the item very popular, which is not the actual case. The effects of such spurious requests from impatient clients needs to resolved. We have developed hybrid scheduling principle which takes care of clients impatience and resolves the anomalous behavior. Performance modelling using birth and death process and *multi-dimensional Markov Chain* is provided to capture an overall estimate of such practical hybrid scheduling principles.

Today's wireless PCS networks classify the clients into different categories based on their importance. The goal of the service providers is to

provide the highest priority clients with maximum possible satisfaction, even at the cost of some lower priority clients. This, in turn, helps in reducing the overall churn rate and increasing the overall profit of the service providers. The role of clients priorities needs to be considered to implement such *differentiated QoS*. We have introduced a new service classification scheme in our hybrid scheduling strategy which combines the stretch-optimal and priority-based scheduling in a linear fashion to develop a new selection criteria, termed importance factor. While the items to be pushed are determined using a flat scheduling, the item from the pull queue is selected based on this *importance-factor*. Modelling and analysis of the system is performed to get an average behavior of the QoS parameters like delay, bandwidth and drop-request in this new hybrid scheduling framework. The dissertation proceeds further to investigate into the hybrid scheduling over multiple channels. It is shown that using online partitioning of data items into multiple channels and deploying hybrid schedule on every channel has the power to improve the average waiting time of the clients over the existing optimal multi-channel push-based scheduling schemes.

While the wireless communication technology is rapidly enhancing from a voice-alone framework to an audio-visual world of real-time applications, the efficiency of data broadcasting needs to be improved significantly. The gradual deployment of 3G wireless systems and the quest for 4G wireless systems has encouraged us to look and investigate into different open problems in data broadcasting. In future we want to look into the effects of efficient data caching mechanisms to save the energy of the power-constrained mobile devices. The dynamism of the wireless networks and Internet often creates uncertainty and variation of the QoS parameters. We believe that the QoS offered in wireless networks and Internet should not be constant, but needs to change over the time. Thus, in order to provide the services

with some level of QoS guarantee, the QoS parameters need to be re-negotiated at specific intervals. We would like to look into the effects and solutions required to design such re-negotiable QoS in data broadcasting over wireless systems and the Internet.

Bibliography

- [1] S. Acharya, R. Alonso, M. Franklin and S. Zdonik, “Broadcast Disks: Data Management for Asymmetric Communication Environments”, *Proc. of ACM SIGMOD*, 1995.
- [2] S. Acharya, M. Franklin and S. Zdonik, “Balancing Push and Pull for Data Broadcast”, *Proc. of ACM SIGMOD*, 1997.
- [3] S. Acharya and S. Muthukrishnan, “Scheduling On-demand Broadcasts: New Metrics and Algorithms”, *Proc. ACM Intl. Conf on Mobile Computing and Networking (MobiCom)*, 1998.
- [4] D. Aksoy and M. Franklin, “Scheduling for Large-Scale On-Demand Data Broadcasting”, *Proc. of IEEE InfoCom*, 1998.
- [5] D. Aksoy and M. Franklin, “RxW: A Scheduling Approach for Large-Scale On-Demand Data Broadcast”, *IEEE/ACM Trans. on Networking*, vol. 7, No. 6, pp. 646-860, 1999.
- [6] D. Aksoy, M. Franklin and S. Zdonik, “Data Staging for On-Demand Broadcast”, *Proc. of 27th VLDB Conference*, 2001.
- [7] A. Bar-Noy and Y. Shilo, “Optimal Broadcasting for Two Files over an Asymmetric Channel”, *Journal of Parallel and Distributed Computing*, vol. 60, no. 4, pp. 474-493, 2000.

- [8] A. Bar-Noy, J. S. Naor and B. Schieber. Pushing Dependent Data in Clients-Providers-Servers Systems. In *Mobile Networks and Applications*, Vol. 9, pages 421-430, 2003.
- [9] A. Bar-Noy, B. Patt-Shamir and I. Ziper, "Broadcast Disks with Polynomial Cost Functions", *ACM/Kluwer Wireless Networks (WINET)*, vol. 10, pp.157-168, 2004.
- [10] A. Bar-Noy, B Patt-Shamir and I. Ziper, "Broadcast Disks with Polynomial Cost Functions", *ACM/Kluwer Wireless Networks (WINET)*, vol. 10, pp. 157-168, 2004.
- [11] Z. Brakereski and B Patt-Shamir, "Jitter -Approximation Tradeoff for Periodic Scheduling", *Proc. of IEEE Intl. Workshop of WMAN*, 2004.
- [12] A. A. Bertossi, M. C. Pinotti, S. Ramaprasad, R. Rizzi and M. V. S. Shashanka, "Optimal Multi-channel Data Allocation with Flat Broadcast Per Channel", *Proc. of IEEE IPDPS*, 2004.
- [13] S.E. Czerwinski, B.Y. Zhao, T.D. Hodes, A.D. Joseph, and R.H. Katz, "An Architecture for a Secure Service Discovery", *Proc. 5th Int. Conf. Mobile Computing (Mobicom)*, pp. 24-35, Aug. 1999.
- [14] M. Franklin and S. Zdonik, "A Framework for Scalable Dissemination-Based Systems" *Proceedings of the 12th ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications*, pp. 94 - 105, 1997 .
- [15] Q. Fang, V. Vrbsky, Y. Dang and W. Ni, "A Pull-Based Broadcast Algorithm that Considers Timing Constraints", *Proc. of Intl. Workshop on Mobile and Wireless Networking*, 2004.

- [16] J. Fernandez and K. Ramamritham, “Adaptive Dissemination of Data in Time-Critical Asymmetric Communication Environments”, *Euro-micro Conf. on Real-time Systems (ECRTS)*, 1999.
- [17] D. Gross and C. M. Harris, Fundamentals of Queuing Theory, *John Wiley & Sons Inc.*
- [18] Y. Guo, S. K. Das and M. C. Pinotti. A new Hybrid Broadcast scheduling Algorithm for Asymmetric Communication Systems: Push and Pull Data based on Optimal Cut-Off Point. In *Mobile Computing and Communications Review (MC2R)*, Vol. 5, No. 4, 2001.
- [19] S. Hameed and N. H. Vaidya. Efficient algorithms for scheduling data broadcast In *Wireless Networks*, Vol. 5, pages 183-193, 1999.
- [20] W-C. Lee, Q. Hu and D. L. Lee, “Channel Allocation Methods for Data Dissemination in Mobile Computing Environments”, *Proc. of Intl. Symp. on High Performance Distributed Computing (HPDC)*, 1997.
- [21] Q. Hu, D. L. Lee and W-C. Lee, “Performance Evaluation of a Wireless Hierarchical Data Dissemination Systems”, *Proc. of AGM MobiCom*, 1999.
- [22] C-L. Hu and M-S. Chen, “Adaptive Information Dissemination: An Extended Wireless Data Broadcasting Scheme with Loan-Based Feedback Control”, *IEEE Trans. on Mobile Computing*, vol. 2, no. 4, 2003.
- [23] <http://www.direcpc.com>, 1997
- [24] S. Jiang and N. H. Vaidya, “Scheduling Data Broadcast to “Impatient” Users, *ACM Intl. Workshop on Mobile Data Engineering*, 1999.

- [25] C. Kenyon, N. Schanbanel and N. Young, “Polynomial-Time Approximation Scheme for Data Broadcast”, *Proc. of ACM Symp. on Theory of Computing (STOC)*, 2000.
- [26] S. Khanna and V. Liberatore, “On Broadcast Disk Paging”, *Proc. of ACM STOC*, 1998.
- [27] Q. Hu D. L. Lee and W-C. Lee, “Optimal Channel Allocation for Data Distribution in Mobile Computing Environments”, *Proc. of Intl. Conf. on Distributed Computing Systems (ICDCS)*, 1998.
- [28] W-C. Lee, Q. Hu and D. L. Lee, “A Study on Channel Allocation for Data Dissemination in Mobile Computing Environments”, *Mobile Networks and Applications (MONET)*, vol. 4, pp. 1‘7-‘29, 1999.
- [29] G. Lee and S. C. Lo. Broadcast Data Allocation for Efficient Access of Multiple Data Items in Mobile Environments. In *Mobile Networks and Applications*, Vol. 8, pages 365-375, 2003.
- [30] C-W. Lin, H. Hu and D-L. Lee, “Adaptive Realtime Bandwidth Allocation for Wireless Data Delivery”, *ACM/Kluwer Wireless Networks (WINET)*, vol. 10, pp. 103-120, 2004.
- [31] W. Ni, Q. Fang and S. V. Vrbsky, “A Lazy Data Approach for On-demand Data Broadcasting”, *Pro.c of 23rd Intl. Conf. on Distributed Computing Systems Workshops (ICDCSW03)*.
- [32] JH. Oh, K. A. Hua and K. Prabhakara, “A New Broadcasting Technique for An Adaptive Hybrid Data Delivery in Wireless Mobile Network Environment”, *Proc. of IEEE Intl. Performance Computing and Communications Conf.*, pp. 361-367, 2000.

- [33] W-C Peng, J-L Huang and M-S Chen, “Dynamic Leveling: Adaptive Data Broadcasting in a Mobile Computing Environment”, *ACM/KLUWER Mobile Networks and Applications*
- [34] M. C. Pinotti and N. Saxena. Push less and pull the current highest demanded data item to decrease the waiting time in asymmetric communication environments. In *4th International Workshop on Distributed and Mobile Computing, (IWDC)*, Calcutta, India pages 203–213. Springer-Verlag 2002; LNCS 2571, Dec 28-31, 2002.
- [35] N. Saxena, K. Basu and S. K. Das, “Design and Performance Analysis of a Dynamic Hybrid Scheduling for Asymmetric Environment”, *IEEE Intl. Workshop on Mobile Adhoc Networks, WMAN*, 2004.
- [36] N. Saxena and M. C. Pinotti, “Performance Guarantee in a New Hybrid Push-Pull Scheduling Algorithm”, *Third International Workshop on Wireless Information Systems (WIS)*, 2004.
- [37] N. Saxena, M. C. Pinotti and S. K. Das, “A Probabilistic PushPull Hybrid Scheduling Algorithm for Asymmetric Wireless Environment”, *IEEE Intl. Workshop on Wireless Ad Hoc and Sensor Networks* (co-located with GlobeCom), 2004.
- [38] N. Saxena, K. Basu, S. K. Das and M. C. Pinotti, “A Prioritized Hybrid Scheduling for Two Different Classes of Clients in Asymmetric Wireless Networks”, *To Appear in 24th IEEE. International Performance Computing and Communications Conference (IPCCC)*, 2005.
- [39] N. Saxena, K. Basu, S. K. Das and M. C. Pinotti, “A New Hybrid Scheduling Framework for Asymmetric Wireless Environments with Request Repetition”, *To Appear in 3rd IEEE Intl. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, 2005.

- [40] N. Saxena and M. C. Pinotti, “On-line Balanced K-Channel Data Allocation with Hybrid Schedule per Channel”, *Under Review in IEEE Intl. Conf. in Mobile Data Management (MDM)*, 2005.
- [41] N. Saxena, K. Basu, S. K. Das and M. C. Pinotti “A Dynamic Hybrid Scheduling Algorithm for Heterogeneous Asymmetric Environments”, *To Appear in International Journal of Parallel, Emergent and Distributed Systems (IJPEDS)*, Feb. 2005.
- [42] N. Saxena, K. Basu, S. K. Das and M. C. Pinotti, “A New Service Classification Strategy in Hybrid Scheduling to Support Differentiated QoS in Wireless Data Networks” *under review in IEEE IPCC*, 2005.
- [43] N. Saxena and M. C. Pinotti, “A Dynamic Hybrid Scheduling Algorithm with Clients’ Departure for Impatient Clients in Heterogeneous Environments” *5th IEEE International Workshop on Algorithms for Wireless, Mobile, Ad Hoc and Sensor Networks (WMAN)* 2005.
- [44] A. Seifert and M. H. Scholl, “Processing Read-Only Transactions in Hybrid Data Delivery Environments with Consistency and Currency Guarantees”, *ACM/Kluwer Mobile Networks and Applications (MONET)*, vol. 8, pp. 327-342, 2003.
- [45] C-J. Su, L. Tassiulas and V. J. Tsotras, “Broadcast Scheduling for Information Distribution”, *ACM/Kluwer Wireless networks (WINET)*, vol. 5, pp. 137-147, 1999.
- [46] W. Sun, W.Su and B. Shi, “A Cost-Efficient Scheduling Algorithm of On-demand Broadcasts”, *ACM / Kluwer Wireless Networks (WINET)* 2003.
- [47] “Support of Third Generation Services Using UMTS in a Converging Network Environment”, *UMTS Forum*, 2002.

- [48] N. Vaidya and S. Hameed. Log time algorithms for scheduling single and multiple channel data broadcast. *Proc. Third ACM-IEEE Conf. on Mobile Computing and Networking (MOBICOM)*, pp. 90-99, September 1997.
- [49] N. H. Vaidya and S. Hameed Scheduling data broadcast in asymmetric communication environments In *Wireless Networks*, Vol. 5, pages 171-182, 1999.
- [50] N. Vlajic, C. C. Charalambous and D. Makrakis, "Performance Aspects of Data Broadcast in Wireless Networks with User Retrials", *IEEE Transactions on Networking*, Vol. 12, No. 4, pp. 620-633, 2004.
- [51] J. Xu, D.L. Lee, Q. Hu, and W.C.Lee, "Data Broadcast", *Handbook of Wireless Networks and Mobile Computing* , I. Stojmenovic, Ed., New York: Wiley, 2003
- [52] P. Xuan, S. Sen, O. Gonzalez, J. Fernandez and K. Ramamritham, "Broadcast on Demand: Efficient and Timely Dissemination of Data in Mobile Environments" , 1997.
- [53] W. G. Yee, S. B. Navathe, E. Omiecinski and C. Jermaine, "Efficient Data Allocation over Multiple Channels at Broadcast Servers", *IEEE Trans. on Computers*, vol. 51, no. 10, pp. 1231-1236, 2002.
- [54] W. G. Yee and S. B. Navathe, "Efficient Data Access to Multi-channel Broadcast Programs", *Proc. of ACM Conf. on Intl. Knowledge Management, (CIKM)*, pp. 153-160, 2003.