DSearch: Distributed search for a personal area network

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ABSTRACT

Searching through a user's distributed data set effectively is crucial. User created content is increasingly stored on multiple devices away from home. Conventional desktop search and distributed file systems have relied on kernel modules and practically unlimited resources to organize and search user content. These designs do not consider the complex set of constraints and challenges in the distributed search domain. We propose a distributed architecture, *DSearch*, to manage the complexities of a mobile data set to improve query performance across all the devices in a user's personal area network. First, we provide a light-weight infrastructure that can effectively organize and search a set of devices. Second, we develop a membership system to manage the dynamics of multiple devices in a network that records the current set of active devices and distributes information to the group. Third, we examine three search index replication schemes - no replication, centralized replication, and device-based replication - to improve query performance. We developed the DSearch distributed system and evaluated its performance.

1. INTRODUCTION

Searching through a user's distributed data set effectively is crucial. User created content is increasingly stored on multiple devices away from home. In fact, it has been estimated that 55% of all digital information resides on personal computers [12]. Furthermore, individuals continue to purchase new cell phones, laptops and hand held devices with ever growing memory capacities and functional specializations, increasing physical location diversity. Previous search architectures tuned for single, stationary devices are not effective at managing the challenges associated with querying data across heterogeneous machines. To support the changes in personal data storage patterns, alternative search organizations are necessary. This paper proposes a distributed search architecture, *DSearch*, for multiple mobile devices in a user's personal area network.

Conventional desktop search and distributed file systems have relied on kernel modules and practically unlimited resources to organize and search user content. These designs do not consider the complex set of constraints and challenges in the distributed search domain. Specifically, these systems take for granted devices' physical location, varied connection capabilities and intermittent periods of connectivity. Also, complex file systems assume the presence of a particular operating system running on a high-powered processor, in contrast to extremely heterogeneous mobile devices that have limited processing power. Given these constraints, we examine the best way to replicate search indexes within a user's personal area network for improved query performance and power efficiency.

We propose a distributed architecture, DSearch, to manage the complexities of a mobile data set to improve query performance across all the devices in a user's personal area network (PAN). First, we provide a light-weight infrastructure that can effectively organize and search a set of devices. Because of mobile devices' limited computation abilities, full-fledged data indexing mechanisms are not practical. Second, we develop a membership system to manage the dynamics of multiple devices in a PAN that records the current set of active devices and distributes information to the group. We leverage a socket abstraction to manage our network communication.

Third, we examine three search index replication schemes to improve query performance. In the basic, no replication architecture, queries are sent to each active device in the PAN. Every device in this configuration searches its own content and responds with a list of matching files. The basic design limits search performance since the slower devices are queried and must be waited on for complete query aggregation. A centralized architecture improves on the basic design by replicating all search indexes to a coordinator, which is assumed to be always-on, although this does introduce a single bottleneck and point-of-failure. For each query, only the coordinator is sent a request and computational slower devices are bypassed. Lastly, we provide a device-based replication scheme that allows each machine to select which other devices' search indexes to store locally based on query latency. We vary the number of replicas that can be stored at each device and examine the query time for all the designs.

This paper makes the following contributions:

- **Light-weight search infrastructure.** Python based application architecture that runs on desktops, laptops and mobile devices.
- **Dynamic membership management.** System to manage the arrival, departure, and intermittent connectivity of devices in the personal area network.
- **Search index replication for improved query performance.** Three replications architectures (no replication, centralized replication, device-based replication) tested and evaluated for query performance.

In Section 2 we provide a brief summary of the background in search systems and discuss related work. We go into more detail on DSearch itself in Section 3, and describe the implementation in very granular detail in Section 4. We layout a graphical model of our replication optimization scheme in Section 5 and evaluate our system in Section 6. Lastly we give our conclusion in Section 7 and future work proposal in Section 8.

2. BACKGROUND AND RELATED WORK

Personal file search systems are now common; Windows Desktop Search [1], Google Desktop [10], Apple's Spotlight [16], and the open source project Beagle [5] are several examples. Each maintains an up-to-date index of the user's content, allowing them to quickly find matching content based on a search query. However, as users tend to own multiple devices, content is often spread across those devices, and there is no unified interface from which to search the user's "cloud" of devices.

A distributed search system is one that allows a user to query a set of devices from any one of those devices and retrieve search results, identifying files and the devices on which they are located. Each device is responsible for the content it "owns" and therefore should maintain its own index. Such a system would need to have mechanisms for devices to join and leave the system, to locate other devices in the system and exchange messages with them, and to distribute query requests and aggregate query results. The distributed search system is similar to the aforementioned desktop search systems in that each device can be seen as an independent desktop search service, but the distributed system must provide means to share the individual devices' search results among all members of the system.

Various approaches have been applied to distributed search thus far. For instance, some work has been done on expanding the traditional distributed file system to effectively address needs of more consumer electronics devices [13]. Others have approached the problem from the other end, starting with the intermittently connected mobile devices and trying to maintain or impose some overlaying structure. Flinn and Anand proposed PAN-on-Demand, a self-organizing overlay network scheme which utilizes differing radio capabilities and device heterogeneity for the ultimate goal of achieving excellent power usage [2]. Differing modes of membership have also been proposed and some studies have focused on the cost differences between real-time discovery versus connection maintenance [2]. Others have focused on the potential performance gains of using multiple interfaces (e.g., Bluetooth and WiFi) simultaneously while operating at the application layer [3] or by modifications at the transport layer [11].

Similarly, researchers have also proposed various ideas for distributing data to multiple mobile devices [17] as well as the potential performance benefits from caching data on a device-by-device basis [12]. Consideration has been given to the importance of how data is stored or distributed across a p2p network in order to preserve locality of data while still maintaining effective and scalable query throughput [14]. Other approaches have aggregated a user's devices into a single addressable virtual device focusing on higher level "person-level routing" [6, 4], while others have focused on lightweight development frameworks [15].

3. DSEARCH

An increasing amount of data is being stored on mobile devices with growing storage capacity and functional specializations. Similarly, users now own an increasing number of devices, dividing their content among them. As a result, the ability to search through a user's mobile data set becomes important. Unlike desktop search, however, searching a network of mobile devices presents a different set of constraints and challenges due to devices' locational diversity, varied connection capabilities, intermittent periods of connectivity and device heterogeneity.

First, because of the limited computational capacities of these devices, full fledged data indexing mechanisms are not practical. Instead, there is a need for a light-weight indexing infrastructure that can effectively target these devices. Second, personal devices are by nature mobile, and any system that searches among these devices needs to consider intermittent availabilities and changes in the location of devices. This calls for a technique for managing the personal area network (PAN) and identifying and maintaining members of the group. These and other challenges make distributed mobile search an interesting domain to work in.

We developed DSearch, a light-weight distributed search application. DSearch manages devices leaving and joining the network. We provide a basic infrastructure to search content on all the connected devices and provide three search index replication schemes to evaluate their impact on query performance.

4. DSEARCH IMPLEMENTATION

DSearch is a Python application that runs on each device in the PAN. Our system is platform independent and only requires that Python and SQLite be installed on each device. The implementation operates on Mac OS X and Linux based operating systems. Python was specifically chosen since it is good for quick development and prevalent on a wide variety of platforms. Python scripts do not execute as fast as statically typed, compiled programs, but we chose it for its portability and ease-of-use.

One device acts as the coordinator of the PAN. This device is assumed to be always-on and has a high-performance processor. Various settings control the type of replication scheme, the port to listen on and the address of the coordinator. When DSearch is started at a device, the system

registers with the coordinator and is assigned an identification number, which is distributed to all other active members along with other member information. The coordinator keeps track of devices as they leave and rejoin the network.

The owner of the device interacts with DSearch through a command-line interface. This interface allows the user to specify directories to be indexed to satisfy future queries. Queries are initiated through the command-line interface. The DSearch architecture multiplexes the query to the other members of the PAN depending on the replication scheme. All search indexes in the PAN are examined on each query. Our current implementation does not incorporate query history into the search model and does not provide any prequery filtering to reduce the number of empty results. Results are aggregated and ranked locally and displayed to the terminal.

The DSearch implementation is divided into four categories: communication systems, data management, membership management, and searching infrastructure. The communication system provides the networking interfaces for DSearch. The data management system indexes local data and stores it for future queries. The membership module manages the dynamic joining and leaving of members in the group. The search infrastructure implements the basic query system as well as three search replication schemes.

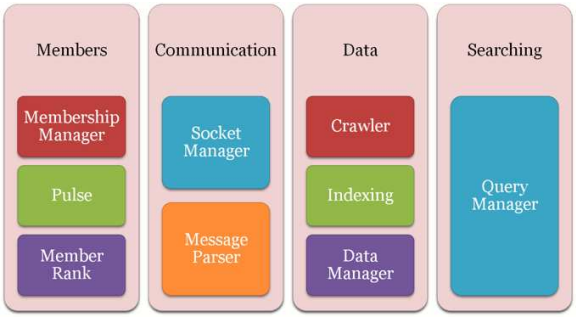


Figure 1: DSearch High Level Design

4.1 Communication

We developed a network layer abstraction over the Python socket module to manage all DSearch network connections. The *socket manager* listens on a specified port for incoming messages and provides functionality to send data to members in the PAN through TCP connections. All modules within the DSearch architecture that require network communication utilize the socket manager. This design approach unifies all socket programming in a single location and creates a uniform message format for all data communications, an important objective for a developer within a pervasive environment [15].

We use function-callback semantics for all network communication. On the send of data, the developer provides the socket manager with a reference to a function to process causally-related received messages. All data sent to and received from the socket manager is organized into text buffers, thus greatly reducing the complexity of interacting with TCP sockets. Furthermore, to simplify our network interactions, we developed a messaging module that converts Python structures into XML messages and transforms XML text strings into Python structures. For future iterations, we will consider a less verbose message protocol to better suit mobile devices' resource constraints. However, this construction allows us to easily send and receive data structures over the wire while also making it easy to read and debug the messages being sent and received.

4.1.1 *Consideration of Tradeoffs*

DSearch pushes the message delivery guarantee down into the network stack and does not provide strict message ordering. We utilize TCP sockets to ensure reliable delivery of messages between the devices in the PAN. Python provides an easy interface to TCP sockets, therefore allowing us to push the delivery details down into the network stack. We do not provide any message order guarantees such as causal or total ordering. Specific message ordering is not necessary since all messages are idempotent and are independent of the order in which they are executed. As a result, some devices may have different views of the PAN. Varied views are acceptable for short durations in a distributed search application as query results will contain subsets of the entire result space and individual views eventually converge.

4.2 Data Management

The Data Manager provides a mechanism to examine file content and provides a search facility. Search systems usually use some variation of an inverted index, in which keywords map to files containing those words. We take a similar approach in DSearch. Since our system involves several devices storing different content, our index maps keywords to $(memberId,\ filepath)$ pairs, where a $memberId$ (assigned by the coordinator) identifies a member uniquely within the system.

4.2.1 *Index Manager*

The IndexManager maintains a list of root directories that are currently being indexed. On program startup, the IndexManager spawns a thread and scans through each of the directories in the list recursively, looking for keywords and adding mappings to the index. The user can add and remove directories through the command-line interface, and the index is immediately updated in response to those commands. In the absence of add and remove requests, the IndexManager thread will periodically wake up and refresh the index by scanning all the root directories and repopulating the index structure.

4.2.2 *Data Manager*

The DataManager module implements the backend data structure used by our indexing mechanism: a SQLite3 database. We chose this approach both to speed development and because SQLite3 is available on our handheld device and in the default Python installation. The DataManager abstraction includes methods to insert (word, file) matches as the IndexManager thread processes files. In addition, the DataManager provides a method to construct an XML message, encapsulating the index structure it stores, to be sent to other members upon request. This functionality forms the bedrock for our index replication strategies, as follows.

4.2.3 Index Shipping

In order to allow members to request and receive search index replicas, the IndexManager keeps a list of *subscribers*, or members who have requested this member's index. Upon receiving a *requestIndex* message, the IndexManager adds the requester to the subscribers list if it is not already present and responds by sending an XML message containing its index. From then on, whenever the member updates its index (whether periodically or due to a user command), it will re-send its index to all of its subscribers. Though this is more costly than sending incremental index updates, it also greatly simplifies the message-passing semantics, since each index update sent to a subscriber is idempotent.

4.2.4 Consideration of Tradeoffs

As we designed our search and indexing mechanisms, some clear tradeoffs presented themselves. First, there is a significant computational cost involved in crawling through directories and extracting keywords from files. Initially, this cost is compulsory; the first time a directory is added to the index, the content has never been seen before and must be scanned and read completely. After the initial scan, however, it is sufficient to only re-scan files that have changed since the last scan. The general point is this: by updating the index (with a full re-scan) frequently, we increase the likelihood that searches have the most up-to-date view of the indexed content, but with the computational cost incurred by frequent scans.

Second, there is a clear tradeoff between the size of the index and the robustness of the search. Currently, we keep a count of the number of times each keyword appears in each file, but we do not store any positional data (for example, to allow searching for phrases). Whereas most personal file search systems are first optimized for speed, a search system intended for deployment on mobile devices must carefully consider how much storage to spend in return for better query results. Given our simplistic indexing implementation, we defer a rigorous exploration of this tradeoff to future work, though it is worth noting that our current indexing mechanism requires an 924KB database to index the content of 22 files totaling 26MB in size.

Third, since we are targeting mobile devices with limited computational, storage, and power resources, there is an important tradeoff between the spending of those resources on frequent and thorough indexing and the freshness and robustness of search results from the mobile device. Crawling directory structures and reading many files is particularly slow and costly on mobile devices, and we would like to do this work as infrequently as possible. As discussed previously, however, infrequently updating the index may lead to stale search results, depending on how quickly the searched data set is changing. Also, as the size of the total content being indexed on a mobile device grows, the database queries involved in finding keyword matches become more costly. It is at this point that shipping indexes to more well-provisioned (e.g. 2GHz, 2GB RAM, AC power vs. 400MHz, 128MB RAM, battery power) devices becomes attractive, since avoiding executing the query at the mobile device will save time and power.

A key consideration in making the decision whether to ship an index is the rate of queries vs. the rate of content updates. If the query-to-update ratio is high, then it probably will benefit the mobile device to ship its index to a more powerful device; if the ratio is low, it may not make as much sense, since the device may spend more time sending indexes than responding to query requests, resulting in an overall loss. Though we do not currently incorporate these considerations into our system, it would be a high priority for future work.

In the design of DSearch data management modules, our aim was only to provide the base functionality required to index and search file content; we were not concerned with providing the robustness of a consumer desktop search application. We speculate that a more polished indexing and searching backend could be easily incorporated into our system in the future, given our highly modular design.

4.3 Membership Protocol

As a distributed search system, DSearch needs to manage its members in an efficient manner. One of the basic assumptions that we made while designing the membership management modules for DSearch is that one of the members will act as the coordinator and the other members will have to register with the coordinator to be part of the system. Because of the way the code is implemented, any one of the members could act as the coordinator. However, we have not currently implemented an election algorithm for DSearch. We imagine either the token passing algorithm or the bully algorithm [8] could be easily plugged into the system.

There are two membership management modules in DSearch. The first is aptly called Membership Manager and the other is called Pulse. Membership Manager is the global membership manager that handles member registering, ID assignment and member list distribution. It also supplies Pulse with new information about the system as it becomes available.

After one device is started as the coordinator for the system, other devices can register themselves using their IP address and port. When the coordinator receives a register request from a device, it looks up its members list and assigns the new device a unique ID, which is broadcast to the rest of the system along with the new device's IP and port. With this information, devices can set up TCP connections to other members in the group. In the current implementation of DSearch, IDs are not persistent, although persistence could be added in the future. Any device registering from the same IP and port is guaranteed to have the same ID as long as the coordinator was alive between sessions. Membership Manager also defines the basic object that is used to fully characterize a member. This object is easily extensible to handle any future improvements on DSearch. The properties defined in the Member Info class could be used to determine the best way to connect to a device considering factors like context and proximity. Finally, Membership Manager provides a basic n-way unicast mechanism to reach members, although this role is often taken by Pulse for liveliness reasons as we will discuss in the next paragraph.

Pulse is the activity manger of the system. It maintains a current view of the system from a particular device rather

than the global state kept in Membership Manager. The basic mechanism used to achieve this is heartbeat messages sent periodically from the members to the coordinator. A member is allowed a few cycles of "grace" to send its heartbeat to the coordinator before deemed inactive. This value, set by the administrator of the system, determines how long a coordinator waits before removing a member from the active list, and hence it also determines the upper bound on how long the active member list could be stale on any particular device. Setting the grace to be higher will give member a longer duration to reconnect to the system with out having to go through the registration process again. This might be especially important in mobile devices where the connections are likely to be intermittent. On the other hand, setting the grace to be smaller gives a more current view of the system at any given time at the expense of re-registering.

Pulse propagates the active list to the members in one of two modes. The default mode is event triggered, in which the active list is distributed to members whenever an event occurs on the coordinator that changes the current active list; these are mainly leaves and joins. The other mode is an on-demand mode in which a member receives the active list only when needed, either to make caching decisions or to send out messages. When a member receives the active list, it also gets a lease time on the current active list, which is as long as the grace. If the list is any older, a member will have to request it again. Setting the lease to be equal to the grace makes sense because that is also the earliest a coordinator publishes the deletion of a device from the members list.

The on-demand mode is most efficient when the join/leave rate is much higher than the rate of requests for the active list. By requesting the active list only when needed, members avoid getting unnecessary updates that are potentially going to be out of date soon. On the other hand, when there is low join/leave activity on the system, event-triggered updates is more appropriate because the list distributed is potentially going to be useful for a while.

Pulse exposes a variety of methods that can be invoked to learn about the current state of the system. Pulse also provides a way to send messages to active members implemented using an n-way unicast. The sending mechanism provided by Pulse is used to connect to the most up-to-date list of members known by the system. It is important to note that Pulse runs in its own thread of execution than the main thread, and is synchronized to the main thread using basic primitives provided by Python.

4.4 Query Management

We created a single module responsible for distributing queries to all active members of the DSearch network as well as merging and aggregating the individual responses into a easy-to-read summary. The current implementation defines a query as one or more text terms which are associated with a file (either explicitly such as in a text document or PDF file or more loosely such as the metadata of an MP3 file). As with other user commands in the system, queries are entered in through the console.

4.4.1 Query Distribution

The goal of query distribution is to efficiently disseminate a user's query to all currently active members of the DSearch network. To that effect, how exactly this is accomplished varies significantly depending on the replication scheme being used. With the default no-replication scheme, the query is sent to each active member of the network who is entirely responsible for his own indexed content. When utilizing the centralized replication scheme, a single query is sent to the coordinator with the specification to search across all indexes on behalf of all members, in essence a global system search is performed locally by the coordinator. Lastly, with the device-based replication scheme, queries are distributed strategically to exploit the more efficient processing capability or lower network latency exhibited by certain members of the network. Regardless of the replication scheme, every member of the current system is queried either directly or indirectly and its response is required before the query search results are presented to the user.

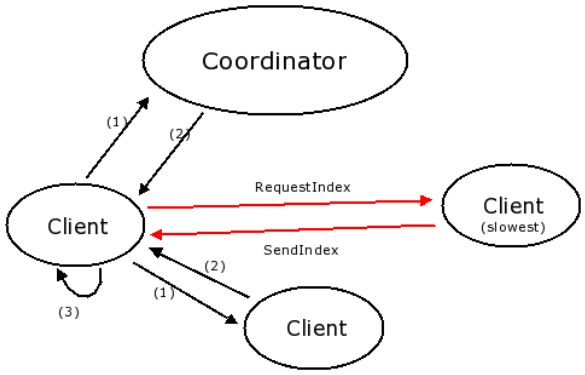
As a side note, there is a querying capability to allow the user to query only a specific device. This is useful in situations where the user is only interested in files residing on a laptop or MP3 player rather than all devices. This feature meshes as expected with the various replication schemes as only the member responsible for the device specified is queried.

4.4.2 Query Response Aggregation

Utilizing the Socket Manager's callback functionality, a cumulative query aggregation function is utilized once a query response is returned to the issuer. After distribution, the issuer knows how many responses are expected and will wait until it has received either a valid response or some type of notification that the user is disconnected from everyone before continuing. It should be noted that since global ordering constraints are not guaranteed in the DSearch implementation as mentioned above, we assume that a single user only issues one query per device at a time (that is does not issue a second query from the same device before the first query results have been collected and processed for the user) otherwise the results may be jumbled and displayed out of order (this assumption could be relieved if we utilized sequence numbers on queries, but this would pull back some of the messaging responsibilities we delegated to the networking protocol, currently TCP). Once all queried devices have responded, the results are ranked according to the believed relevance. Our current ranking scheme orders the results by (*Number of Search Term(s) Found in File*) / (*Total Number of Terms in File*). More complex ranking schemes are certainly feasible, but this metric proved simple and useful enough to satisfy our current requirements. Once the results have been ranked they are displayed to the user through the console as *MemberId* | *Filepath* | *Frequency / Total Terms.*

4.4.3 Consideration of Tradeoffs

Currently all queries are distributed and responses collected for each query issued by the user. Although the user can reprint the results of the last query executed on the given machine, any other query, no matter how many times executed in the past, will be sent across the network consuming bandwidth and incurring some type of network latency. The advantage of this approach is that if queries are infrequent and tend to vary in terms of keywords searched, this method requires no per-device memory allocation or local store in-



The client on the left has requested and received the index of the slowest client. It (1) sends query requests and (2) receives query responses as in the no-replication mode when querying the coordinator and the faster client on the bottom. When querying the slow client, it (3) uses its local copy rather than sending a message to the slow client.

Figure 2: Querying in device-based replication mode

validation requirements. On the other hand, if queries are much more frequent and tend to typically involve common search terms or locality of reference, it has been shown that much more efficient query response and network utilization is possible by using a local store and clever query response schemes [12].

4.5 Replication Schemes

Replication is used in DSearch as a method for improving availability and performance. DSearch replicates search indexes of devices at various places in the system. There are three modes of operation implemented in DSearch. These modes are device-local, which means the selection affects only a particular device, and a system might be made of devices running different modes of replication.

The first mode implements no replication. Each device is responsible for its own index, and whenever a member needs to query the contents of another member, it simply sends a direct network message to it. This is the most obvious way of doing things, and its biggest advantage (besides being simple) is that it always produces up-to-date search results. On the other hand, it generates great amounts of network traffic, and introduces search latency based on that of the slowest device. There is no need for consistency here because indexes are updated in each device as soon as crawling for new data is done.

The second mode is a coordinator replication mode. This mode assumes a coordinator that has a higher network bandwidth and storage capacity. If the coordinator is running this mode, whenever a device registers, it is informed of the mode and requested to ship its index to the coordinator. This is potentially an expensive operation upfront. However this approach might make sense when the coordinator is relatively faster and queries are done at a consistently high rate. In these cases, the up-front cost will be amortized quickly. Once a coordinator has all active members' indexes, all searches are performed at the coordinator. When a device needs to perform a query, it sends a single message to the coordinator, the search is performed on behalf the member, and the results are sent back to it.

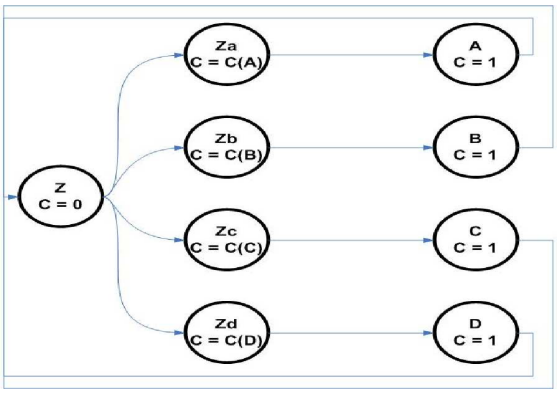
The local replication mode (Figure 2) is a more involved replication scheme than the previous two and is implemented using the Member Rank module. Whenever a device starts up, the user provides a hint for the memory space available for locally caching other device indexes. The Member Rank module sends messages to the active devices requesting what indexes they already have cached. It then uses the round trip time to rank the various members according to the latency. Because DSearch waits for all devices to respond to queries (either with results or some form of notification of a process crash, such as a socket error or timeout), the entire query execution time is as slow as the slowest of the members. So, ideally a member benefits most by replicating the slowest of the devices locally.

However, this is complicated by two issues. First, there is a limit on how many devices each member can replicate, and second there might be faster devices who have already replicated slower devices' indexes, so that it might be faster to use those existing replicas than creating a new one, and instead use the available space to replicate some other device's index. This replication analysis problem is an NP-complete problem that is most similar to the Weighted Directed Dominating Set problem.

DSearch implements an approximation algorithm which puts into consideration these various factors. The algorithm first significantly prunes the search domain and then greedily suggests the best devices to replicate at each step. Although the algorithm is an approximation, this actually plays to our favor because it introduces some randomness into the system. This alleviates the fastest devices in the system from unfairly being overloaded with requests. Once a device determines the best devices to replicate, it requests those member devices to ship their indexes to it.

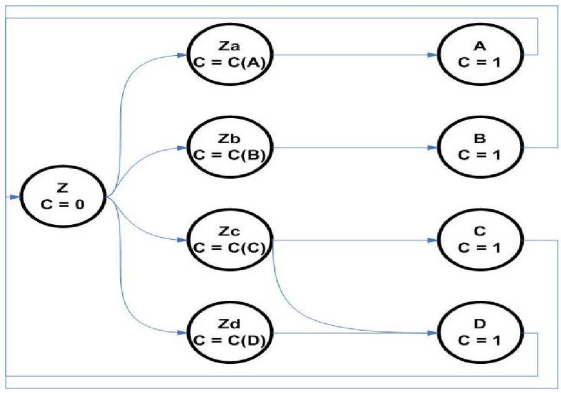
A replication mechanism tailored to the capabilities of individual devices is ideal in a heterogeneous system of devices in which various members have different storage, latency and bandwidth limitations, and has been shown to be very effective [2]. In those cases, local replication tries to find the optimal replication scheme given the current state of the system. It is also interesting to note that under the assumptions for the coordinator replication mode, in which the central device is faster and has plenty of storage space, local replication mode converges to the coordinator replication mode when we are able to replicate all members' indexes locally. By paying a limited upfront cost, a device can minimize its query response time, and upfront cost will be amortized quickly.

In any replication system, it is important to consider consistency among replicas. DSearch uses a primary-based consistency in which one device owns a particular copy of its own index. Also, we notice that DSearch has a unique feature in that only the source of an index ever writes to it, and all other members simply read from it. Because we have an authoritative replica, implementing consistency is straightforward. We achieve consistency using subscriptions to the



In this representation, Z is a new member, A, B, C, D are members already in the system, and an edge from Zx to y represents a replica of y's index at x. This figure shows the system with no replication. The proxy nodes Zx represent the new node Z querying the other nodes, either by sending messages or by querying a local replica of their indexes.

Figure 3: Basic DSearch Graphical Representation



Same as Figure 3, but in this example, C stores a replica of D's index.

Figure 4: Graph Model With Replica

owner of a copy. Whenever a device requests some other member's index, it also subscribes to be notified about any changes in the index. So, after a device re-crawls its folders, it sends its index to all its subscribers. The window of stale indices is then reduced to the time it takes for a network update message from the source to reach subscribers. We believe this is sufficient to get current results in a personal area network.

5. GRAPHICAL MODEL

Selecting the optimal replica to store locally is essential for minimizing query run time. The objective is to select the replica(s) that will maximize the performance gains. Our current implementation uses various techniques such as graph pruning to select which search indexes to store. We present a graphical model that reduces the selection problem to a directed, weighted dominating set problem.

Given a graph, each device must select the optimal replica to store locally. We specify a constant k that determines the maximum number of replicas that can be cached, where k is representative of the device's memory capacity. When a new member joins the network, it subscribes to at most k other devices and receives their search indexes. Each device makes this selection through a calibration technique that ranks the time to get to every device in the PAN and also accounts for other search indexes already replicated to other nodes.

We present a graphical model to assist in this optimization problem. When a device joins the PAN, it creates a graphical representation of the network. Before the graph can be created, all the members of the PAN are ranked based on query latency. Given four members $\{A, B, C, D\}$ with latency costs $1 < C(A) < C(B) < C(C) < C(D)$ and a new node Z with a cost of zero, we create the graph seen in Figure 3. This graph assumes that no replicas have been sent up to this point in time.

The graph is divided into three columns of nodes. The left column contains the new member Z, which has a directed edge to $\{Za, Zb, Zc, Zd\}$. These edges represent device $Z's$ ability to send a query to node X through node Zx. The right column represents the possible replicas that can be stored locally. Our construction only allows k of these nodes can be selected at a time. An edge is added from node Zx to node Y if X has $Y's$ search index stored locally.

To select the optimal replica, we solve the directed, weighted dominating set optimization problem. A dominating set is a set of nodes in the graph such that every node in the graph is either in the dominating set or is connected to a node in the dominating set. For a directed graph, this implies that if A is in the set and there is an edge from A to B, both A and B are covered; however, if the edges goes from B to A, B is not covered by the set. We also must reduce the total cost of the dominating set, which corresponds to the query time. Notice that Z is always added to the set since it has no cost and the cost to store a replica is less than the cost to send a query.

For the case of $k = 0$ in Figure 3, no replicas can be stored and a query must be sent to each device. The dominating set for this network contains $\{Z, Za, Zb, Zc, Zd\}$.

For the case of $k = 1$ in Figure 3, since Zd has the highest cost, it is best to choose the dominating set of $\{Z,\ Za,\ Zb,\ Zc,\ D\}$.

For the case of $k = 1$ in Figure 4 where C already has $D's$ search index stored locally, it is not optimal to store $D's$ search index since it can be accessed more efficiently through C. Therefore, the optimal set is $\{Z, Za, Zc, B\}$. Note that storing C is not optimal since node D would then need to be queried, added the highest possible cost.

The dominating set optimization problem is NP-complete [7, 9]. The reduction is trivial since our representation is a more specified version of the problem. We apply approximation techniques that greedily select the replicas to store. This algorithm runs in $O(N)$ time, where N is the number of members in the PAN.

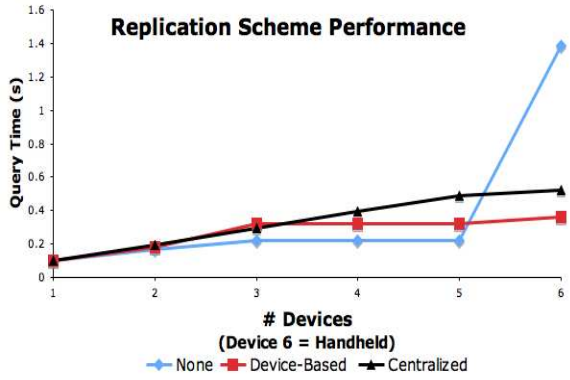


Figure 5: Replication Scheme Performance

6. EVALUATION

6.1 Evaluation Methodology

To analyze DSearch, we preformed a set of experiments to compare the performance of the three replication schemes. We deployed DSearch on multiple Linux and Mac OS X desktops and laptops as well as on one Nokia N800 handheld device. The desktops and laptops had processors clocked from 1.5-2 GHz and had 1-2 GB of main memory compared to the N800's 400 MHz processor and 128 MB of main memory. We measured the total query execution time, defined as the time for all query responses to be received and aggregated at the querying device.

We performed the following tests. First, we measure the query performance as the number of members in the PAN increased while no data was indexed at each device. This test measures how the network performance of the system scales as new members join. We also collected network traffic to measure the growth of the system's bandwidth consumption as the PAN size increases. Second, we gathered performance data for the three replication schemes. We tested the no-replication method, the centralized approach and the device-based scheme and compared their performance. For each of these tests, we indexed a test set of 22 files that included MP3, text and PDF files totaling 26MB in size and requiring an 924KB database. The handheld had a smaller set of files (approximately 688KB) since it takes orders of magnitude longer to index data with the slower processor (e.g. 20 minutes vs. 30 seconds for the same data).

6.2 DSearch Query Performance

First, we analyzed how the DSearch query architecture scaled as devices joined the PAN without any data indexed on the device. Querying empty databases provides us with a bound on the query time and provides insight into the networking costs of a distributed system. When the PAN did not include the handheld device, the query times were extremely small (e.g., 0.008s) and negligible due to the fast interconnects of the LAN. When the handheld was included, query times increased to approximately 0.1 seconds, demonstrating the impact of wireless networks on query performance.

Next, we indexed the data stored on each device and executed queries for the three replication schemes. Figure 5 shows the performance plots for the three designs. The basic, no-replication method issues queries to each device in parallel. When one member is in the PAN, the query is the fastest since no network connection is required. As more devices are added, the query time increases because of the network latency and extra time required to aggregate queries from multiple sources. Note that the query performance remains almost constant when the handheld is not included and when more than one device is in the PAN. Query performance does not vary since each query is issued in parallel and the devices have similar processors. When the handheld joins the PAN, the query time increases by a factor of seven, due to the N800's slower processor and large wireless network latency.

The centralized and device-based replication schemes improve the overall query performance when the handheld is included in the PAN. For the centralized approach, a single query is sent to the coordinator, which then searches in its database for all matching files from throughout the PAN. Since the coordinator contains the aggregate databases from all the devices in the PAN, searching at the coordinator is comparatively slower than the no-replication method. Therefore, for queries not including the handheld, the basic approach outperforms the centralized method, where query time increases almost linearly with the number of devices. However, the centralized method more efficiently processes queries that include the handheld since there is no need to directly query the slower device. Furthermore, the delay from sending indexes is amortized over time due to the improved query performance.

The device-based replication scheme improves on the weaknesses of the centralized model. A drawback of the centralized method is that query time grows linearly with the number of devices, since more data must be searched at the coordinator. We observed from the no-replication model that query time remains constant when multiple, similar performing devices are queried in parallel. Considering this observation, the device-based replication scheme stores a subset of the replicas locally. From Figure 5, we find that the coordinator and device-based methods perform similarly when up to three members are in the PAN, but as more members are added, the device-based replication model maintains a constant performance in contrast to the worsening centralized method. Our observations also hold when the handheld is included in the PAN.

6.3 Alternative Metrics

Shipping search indexes from device to device to improve query performance utilizes more network bandwidth than the no-replication model. When we transfer a search index, we send an XML message containing all the relevant file information stored in the database. For our tests, this message was approximately 140 KB in contrast to approximately 4 KB of data to send and receive query responses from each node with no replication. Since devices are often left on for long durations of time, we believe sending the larger data stream over period of time is an acceptable tradeoff for improved query performance. Also, many mobile devices come with unlimited data plans where this extra bandwidth does not directly cost the user.

Initially, we hoped to measure the N800's power utilization for the various replication schemes. Unfortunately, we were unable to set up the device to perform these experiments. We expect that the power usage would increase when the various replication schemes were utilized. If we tuned DSearch to only index files and send search indexes when the device is connected to AC power, the resulting network configuration would have query performance similar to what we found in the centralized or device-based replication models and not reduce the mobile device's battery life. Since mobile devices are typically plugged in at night, this would be the optimal time to re-index and ship data between the various devices in the PAN.

7. CONCLUSION

We have presented DSearch, a system which enables users to search files distributed across their set of personal devices. We developed three different index replication mechanisms and evaluated their performance, showing that careful index replication can improve query performance and scalability. We feel that DSearch will be a useful framework for future endeavors in managing content in many personal distributed networks with mobile devices.

8. FUTURE WORK

As we have mentioned throughout this paper, there are many ways that DSearch can be expanded to provide better reliability, efficiency, and user interactivity. Instead of relying on a centralized store to keep track of all currently "active" members of the system, it would be more ideal to "discover" other devices when needed [2] or move towards a distributed directory [15] or even a DHT-based approach [14]. Furthermore, for a given user it may be advantageous to provide permanent naming or even name resolution across a unified collection of devices [6, 4]. Clearly, the user would benefit from a more intuitive/graphical user interface. The search capabilities and services offered by DSearch can be strengthened by more advanced indexing schemes or by heterogeneous distribution of indexing responsibilities across the devices [2]. Similarly, querying can be bolstered by allowing looser or "fuzzy" query term matching, more intelligent abstractions of query distribution such as only searching files that can exist on the querying device (e.g., only JPEG files if a camera issues a search), and more relevant or context-aware query response sorting and aggregation. Lastly, the user experience, system reliability, and performance can be enhanced by utilization of other avenues of communication like Bluetooth, Wide Area Network (WAN) Interfaces, and ad-hoc connections [3, 2].

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