ABSTRACT

PUBSUB is a versatile, efficient, and scalable publish/subscribe system. This paper describes the architecture of PUBSUB together with some of its current capabilities. A version of PUBSUB optimized for event processing was benchmarked against the publish/subscribe systems BE-Tree and Siena, which also are optimized for event processing. PUBSUB processes events faster than Siena and BE-tree. On our tests, the speedup of the fastest version of PUBSUB relative to Siena was 98% on an average. The speedup range relative to BE-Tree was from 1.23 to 1.48 and averaged 1.36 for the Zipf tests. The faster times in PUBSUB were a result of very efficient data structures used in PUBSUB to store the subscriptions, and the fast matching algorithms developed to match events to subscriptions.

Keywords
Content based publish/subscribe, Boolean expressions, efficient subscription matching

1. INTRODUCTION

A publish/subscribe (pub/sub) system maintains a database of subscriptions, where each subscription is a Boolean expression. For example, each subscription in the pub/sub system of a diverse online vendor may describe the conditions under which a customer may purchase a product. A customer interested in acquiring a camera may post his/her requirement as a subscription to the vendor’s pub/sub system by providing the Boolean expression:

\[ item = \text{“camera”} \land price < 300 \land manufacturer \in \{ \text{Sony, Nikon, Panasonic} \} \land zoom > 4 \times \]

This subscription uses four attributes of a product, namely, item, price, manufacturer and zoom. An attribute is also referred to as a dimension. A predicate consists of an attribute, an operator and attribute value(s). For each permissible value of an attribute, the predicate evaluates to true or false. In the above example, price $<$ $300$ is a predicate that is true whenever the attribute price has a value below $300$ and false otherwise. A subscription is the conjunction of predicates. Our example subscription is the conjunction of $4$ predicates. An event specifies the values of some attributes. For example the availability of a new $199$ 5x zoom camera from “Sony” or a price change in an existing 5x zoom “Sony” camera to $199$ may be specified by the event:

\[ item = \text{“camera”} \land color = \text{“red”} \land weight = 8 oz \land pixels = 14 M \land price = $199 \land manufacturer = \text{“Sony”} \land zoom = 5 \times \]

The above event matches the example subscription as all $4$ predicates in the subscription evaluate to true when the attributes used in the subscription are assigned the values specified in the event. The example subscription, however, is not matched by the following events:

\[ item = \text{“camera”} \land pixels = 14 M \land price = $399 \land manufacturer = \text{“Sony”} \land zoom = 5 \times \]

\[ item = \text{“camera”} \land price = $129 \land manufacturer = \text{“Sony”} \]

The first of these events fails to match the subscription because the price is too high and the second fails because it does not specify the value of an attribute (zoom) that occurs in the subscription.

When an event occurs, the pub/sub system reports all subscriptions in its database that are matched (or satisfied by the event). Customers who posted these matching subscriptions may then be notified.

Pub/sub systems are used in diverse applications with varied performance requirements. For example, in some applications events occur at a much higher rate than the posting/removal of subscriptions while in other applications the subscription rate may be much higher than the event rate and in yet other applications the two rates may be comparable. Optimal performance in each of these scenarios may result from deploying a different data structure for the subscriptions or a different tuning of the same structure. Many commercial applications of pub/sub systems have thousands of attributes and millions of subscriptions. So, scalability in terms of number of attributes and number of subscriptions is critical.

In this paper, we describe the architecture of PUBSUB, which is a versatile and scalable pub/sub system that may be tuned to provide high performance for diverse application environments. PUBSUB is versatile because its architecture supports a variety of predicate types (e.g., ranges, regular expressions, string relations) as well as a heterogeneous collection of data structures for the representation of subscriptions in order to achieve high throughput. The performance

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of a version of PUBSUB that was tuned for applications in which
events occur far more frequently than subscription posting/deletion
(hence, high-speed event processing coupled with reasonable sup-
port for subscription posting/deletion is required) is compared with
the performance of the pub/sub systems BE-Tree [1] developed by
Sadoghi and Jacobsen and Siena [2, 3], developed by Carzaniga
and Wolf. Both of these benchmark systems also are tuned for the
same application environment. Our extensive experiments show
that PUBSUB processes events up to 95% faster than does BE-Tree
and up to 97% faster than Siena.

We have organized the paper as follows. Section 2 describes the
related work in this area. We present the PUBSUB architecture in
Section 3 and the results of extensive experimental evaluation in
Section 4. We conclude in Section 5.

2. RELATED WORK

The problem of rapidly evaluating a large number of predicates
against specified events has been studied extensively in the litera-
ture. Yan and Garcia-Molina proposed the use of indexes to speed
the evaluation of a collection of Boolean expressions and devel-
oped SIFT [10], which is a system based on indexing. Later vari-
ous researchers proposed decision trees and index structures for
this problem. The proposed approaches can be divided into two main
categories. The first category is counting based while the second
category is based on partitioning subscriptions into subsets. Count-
ing based pub/sub systems build an inverted index structure from
the subscriptions and minimize the number of predicate evaluations
while partitioning-based systems minimize evaluations by recur-
sively eliminating the subscriptions that cannot be satisfied. The
propagation algorithm proposed by Fabret et al. [8], the matching
algorithm proposed by Carzaniga et al. [2, 3], and the indexed list
construction by Whang et al. [9] all result in pub/sub systems that
are counting based. Gryphon, developed by Aguilera et al. [7] and
BE-tree [1] developed by Sadoghi and Jacobsen are examples of
partitioning-based systems. Our pub/sub system, PUBSUB, also is
partitioning based.

BE-tree [1] partitions subscriptions defined on a high dimen-
sional space using two phase space cutting technique, space par-
titioning and space clustering, to group the expressions with re-
spect to the range of values for the various attributes. Experimental
results reported in [1] indicate that the BE-tree outperforms state-
of-the-art pub/sub systems such as SCAN [5], SIFT [10], Propa-
gation [8], Gryphon [7], and k-index [9]. BE-Tree, however, is
limited to attributes whose values are discrete and for which the
range in discrete attribute values is pre-specified. So, BE-tree is
unable to cope with real-valued attributes, string-valued attributes,
and discrete-valued attributes with unknown range. Additionally,
BE-tree employs a clustering policy that is ineffective when many
subscriptions have a range predicate such as $low \leq a_i \leq high$,
where $a_i$ is an attribute and the clustering criterion $p$ that is used
lies between $low$ and $high$. In this case, all such subscriptions fall
into the same cluster and event processing is considerably slowed
as shown in our experiments of Section 4.

Siena [2, 3] is a pub/sub system that uses a counting algorithm
to find matching subscriptions. It maintains an index of attribute
names and types. This index is implemented using ternary search
tries. Unlike BE-Tree, Siena is not limited to discrete valued at-
tributes from a pre-specified finite domain. Further, Siena is able
to work with attributes of type string and supports operators such
as prefix, suffix, and substring on this datatype. Siena, however,
does not support incremental updates (i.e., subscription posting and
deletion) and so updates must be done in batch mode. Although
the present implementation of PUBSUB does not support the string
datatype, its architecture is sufficiently versatile to accommodate
this datatype with the inclusion of additional data structures as
described in Section 3.

3. PUBSUB

Section 3.1 describes how PUBSUB organizes its database of sub-
scriptions. In Section 3.2 the data structures and algorithms used in
PUBSUB are presented.

3.1 Database Organization

Figure 1 gives the organization of the subscription database used in
PUBSUB. This database comprises a collection of level-1 at-
tribute structures $A_1, \ldots , A_m$, where $m$ is the number of attributes.
We assume that the allowable attributes have been numbered 1
through $m$ and that the attributes in a subscription are ordered us-
ing this numbering of attributes. The attribute structure $A_i$ stores
all subscriptions that include a predicate on attribute $i$ but not on
any attribute $j < i$. We say that the attribute $i$ is associated with
the structure $A_i$. With our assumptions on attribute ordering within
subscriptions, $A_i$ contains all subscriptions whose first attribute is
$i$. In practice, many of the $A_i$s will be empty and only non-empty
attribute structures are stored in PUBSUB.

![Figure 1: Organization of PUBSUB subscription database](image-url)

A level-$k$, $k > 0$, attribute structure $A_i$ comprises 0 or more
buckets that contain subscriptions. The distribution of subscrip-
tions across these buckets is determined by the attribute $i$ predi-
cates in these subscriptions and the data structure $D$ used to keep
track of the buckets. The data structure $D$, when given a value $v_i$
for attribute $i$, is able to efficiently locate the buckets that contain
all subscriptions (and possibly others) whose predicate on attribute
$i$ is satisfied by $v_i$. Different attribute structures may use different
data structures $D$ to keep track of their buckets. Individual buckets
of a level-$k$ attribute structure may have higher level (i.e., larger
$k$) attribute structures associated with them. The attribute associ-
ated with a level-$k$ attribute structure is the $k$th attribute of the sub-
scriptions stored in that structure. For uniformity, level-1 attribute
structures are associated with a header bucket that is always empty.

To provide a better understanding of the organization of the sub-
scription database, we describe how events are processed as well as
Algorithm: search(Event $e$, Bucket $b$)
Input:
$e$: event having attributes $e_1, e_2, ..., e_j$
$b$: current bucket, initially the header bucket
Output:
list of matching subscriptions

1: foreach $e_i$, $1 \leq i \leq j$
2: if $A_{e_i}$ is the attribute structure for $e_i$, associated with $b$
3: if ($A_{e_i}$ exists) then
4: $B = $ buckets in $A_{e_i}$ determined by $D$ and $e_i$ to possibly have matching subscriptions
5: foreach $b \in B$
6: add matching subscriptions in $b$ to output list
7: search ($e$, $b$);
8: endif
9: endfor

Figure 2: Search algorithm

how subscriptions are posted and deleted.

Figure 2 gives a high level description of the algorithm to process an event. To search for all subscriptions that match an event that specifies a value for the attributes $e_1 < e_2 < ... < e_j$, we search the level-1 attribute structures $A_{e_i}$, $1 \leq i \leq j$. Note that the remaining attribute structures contain subscriptions that have at least one attribute (i.e., the first attribute) whose value is not specified by the event and so these subscriptions are not matched by the event. To search $A_{e_i}$ for matching subscriptions, we use the associated data structure $D$ to locate the buckets that may possibly contain matching subscriptions. The subscriptions stored in these buckets are examined to determine those that match the event. Additionally, level-2 attribute structures associated with these buckets and whose associated attribute has a value specified in the event (i.e., the associated attribute is one of the $e_i$s) are recursively searched for matching subscriptions. Note that only those attribute structures (regardless of level) whose associated attribute is one of the $e_i$s may be examined when processing an event; the $D$ structures determine which of these are actually examined.

A high level description of the algorithm to post/insert a subscription is given in Figure 3. Using the attributes in the subscription, the attributes associated with attribute structures, and the $D$ structures, we follow a path that begins at the level-1 attribute structure for the first attribute in the subscription, goes to the appropriate level-2 structure for the second attribute, and so on. If no non-empty attribute structure is encountered, then a new level-1 attribute structure with a single bucket is created for this subscription. The attribute associated with this newly created structure is the first attribute of the new subscription. If non-empty attribute structures are encountered, let $k$ be the lowest level at which this happens and let $Z_k$ be the attribute structure encountered at this level. To insert into a level-$k$ attribute structure $Z_k$, the data structure $D$ for this structure is used to determine the appropriate bucket $b'$ of $Z_k$ for insertion. If this bucket is full its subscriptions along with the new subscription are split into 2 or more buckets in accordance with the data structure $D$. In case such a split is not possible (this happens when $D$ is unable to distinguish among the attribute predicates of the subscriptions in the bucket), the next attribute in the new subscription is used to create a new attribute structure that includes the new subscription and all subscriptions in the full bucket that have a predicate on this attribute. When the new subscription doesn’t have a next attribute, we use instead a subscription in the full bucket that has a next attribute. When no subscription has a next attribute we expand the full bucket beyond its designed maximum capacity.

To delete a subscription, we use a procedure that is the inverse of that used to insert a subscription.

3.2 PUBSUB Data Structures

3.2.1 Global Hash Table

A single global hash table is used to keep track of all attribute structures regardless of their level and which bucket they may be associated with. The use of a hash table enables faster branching to a next level bucket than when each bucket stores links to next level buckets. The hash key for an attribute structure $Z_i$ associated with bucket $b$ is the pair $(b, i)$. Each $Z_i$ is kept track of using some characteristic of $Z_i$, such as the header (if any) of the data structure $D$ used in $Z_i$.

3.2.2 Bucket

A bucket is used to store subscriptions. The organization of a bucket is application dependent and we describe exemplar organizations for small and large buckets. Small buckets store few subscriptions, while large ones may store over a thousand subscriptions. Small buckets are useful in applications where the rate at which subscriptions are posted/deleted is high while large ones are useful when we are concerned primarily with the time to process an event.

Subscriptions in a small bucket may be stored as an unordered list. Subscriptions in a large bucket are sorted on the first attribute not associated with the attribute structures on the path from the header to the current bucket. Each group of subscriptions with the same first unused attribute is further sorted based on the predicates of this common attribute. For example, consider a subscription that has a predicate $0 \leq a \leq 10$. Then, the predicate range of attribute $a$ is $[0, 10]$. Subscriptions in a group are sorted by the starting point of the predicate range for the common attribute.

Figure 4 describes the algorithm to find matching subscriptions
Algorithm: Bucket::match(Event $e$)
Input: $e$: event
Output: matching subscriptions
1: $j = 0$;
2: for $i$ // iterate over the subscription groups, increment $i$ by 2
3:    attr = group[i];
4:    groupEndIndex = group[i+1];
5:    if (attr exists in $e$) then
6:        endIndex = binarySearch(attr, $j$, groupEndIndex);
7:        for $j$ up to endIndex, incremented by 1
8:            match $j$th subscription in bucket with event
9:            if (matched) then
10:                append $j$th subscription to output list
11:        endif
12:    endif
13:    else
14:        $j = groupEndIndex + 1$;
15:    endif
16: endfor

Figure 4: Search algorithm for a large bucket

in a large bucket. In this algorithm, we check if the common attribute, which is the first unused attribute for a group of subscriptions in a bucket, is present in the event (line 5). If the common attribute is not present in the event, then the whole group of subscriptions is skipped (line 14). If the common attribute is present, we match subscriptions from the beginning of the group up to a certain subscription given by endIndex (lines 6-7) in the group, thereby skipping the rest of the subscriptions (from endIndex+1 up to groupEndIndex) in that group.

The processed subscriptions have the start points of predicate ranges to the left of the event value, whereas those that are skipped have their start points to the right, which completely eliminates the possibility that the event value will be included in the predicate ranges of the skipped subscriptions. Figure 5 shows a group of 5 predicate ranges and an event value corresponding to the common attribute. The three subscriptions with predicate ranges marked as 1, 2, 3 are matched with the event, whereas those with ranges marked as 4 and 5 are skipped, since the start point of ranges 4 and 5 are to the right of the event value.

In the following, we use the term bucket size to mean the maximum number of subscriptions permitted in a bucket. The actual size (both the number of subscriptions currently in a bucket as well as the number of subscription slots presently available in the bucket; when all subscription slots are occupied, an implementation may expand the bucket using a technique such as array doubling [11]) of a bucket may vary dynamically.

![Figure 5: Predicate ranges are ordered by starting points](image)

3.3 Comparison with BE-Tree

BE-Tree [1] and PUBSUB have many similarities. For example both use clustering on a set of subscriptions that have a common attribute. This is a standard approach for multidimensional data with common attributes and has been used earlier in range trees [20] and multidimensional tries [19], for example. Like BE-Tree, both range trees and multidimensional tries use the same clustering strategy at all levels and for all attributes (range trees use the median attribute value while multidimensional tries use a bit of the attribute to cluster). PUBSUB, on the other hand, allows for a heterogeneous selection of clustering strategies (i.e., the data structure $D$). Both BE-Tree and PUBSUB partition a set of subscriptions into subsets that have a common attribute so that clustering may be applied to these subsets. BE-Tree selects the partitioning attribute by analyzing the subscriptions in the bucket to be partitioned while PUBSUB does this using a pre-specified attribute ordering.

Besides superior performance (see Section 4), PUBSUB offers the following advantages relative to BE-Tree:

1. BE-Tree uses the same clustering strategy for all attributes resulting in a homogeneous system. PUBSUB, which is a heterogeneous system, offers a variety of data structures to keep track of the buckets in an attribute structure enabling the user to select data structures best suited for each attribute.

2. The clustering strategy employed in BE-Tree limits us to attributes whose values are discrete and for which the range of values is known in advance (i.e., at the time the attribute is created). So, for example, a non-negative integer valued attribute can be used only if we know, in advance, what its maximum value is. Because of PUBSUB’s heterogeneity in data structures for each attribute, PUBSUB permits all attribute data types. So, for example, we may set the attribute data structure $D$ to RBPST for all attributes whose values are ordered (i.e., two attribute values may be compared to determine whether one is less than the other or whether both are equal), to IT for discrete valued attributes whose range is known in advance, to suffix tree or Aho-Corasick tries for attributes of string type (although the current implementation of PUBSUB doesn’t support these structures, they are easily added to PUBSUB).

3. The clustering strategy employed in BE-Tree results in performance degradation when many subscriptions specify a range for the clustering attribute that spans the clustering criterion $p$. So, for example, if we are clustering on attribute 6 and us-
4. EXPERIMENTS

The current version of PUBSUB is implemented in C++ and supports, for $D$, the data structures interval tree (IT), and red-black priority search tree (RBPST). For our experiments, we required PUBSUB to use the same data structure $D$ for every attribute structure. As mentioned earlier, users may specify which data structure $D$ should be used for which attribute and, in general, we expect the use of a heterogeneous set of data structures. The terms PS-IT, and PS-RBPST refer to PUBSUB with all data structures $D$ set to IT, and RBPST, respectively. For our experiments, we compiled our code on a 64 bit Linux box with a 1.2GHz CPU. We benchmarked the performance of PUBSUB against the pub/sub systems BE-Tree [1] (July 28, 2012 release) and Siena [2, 3]. The BE-tree release used by us has improved search times over the original version used in [1]. On our platform we got about 10x improvement in search performance of BE-tree with respect to the numbers reported in [1]. We note that the times reported in [1] are in milliseconds while those reported in this paper are in microseconds.

Our experiments, like those of Sadoghi and Jacobsen [1], are for an application environment where the event rate far exceeds the subscription database and then measure the time needed to process an event. This does not include the time needed to process the subscriptions and create the data structure in which the subscriptions are stored (i.e., for example, the time to create the collection of attribute structures used by PUBSUB).

4.1 Determining maximum bucket size

Figure 7 shows how the event processing time varies with maximum bucket size and matching probability.

Bucket sizes $\geq 5000$ result in the best performance for the different matching probabilities as well as for both choices of the data structure $D$. So, for the remaining experiments, we set the maximum bucket size to 5000. We note that in application environments where the subscription insert/delete rate is not low, a smaller bucket size will most likely result in overall best performance.

4.2 How search time varies with the number of subscriptions

Figure 8 gives the variation in event processing time as we increase the number of subscriptions. For the uniform tests the reduction in event processing time using any of the PUBSUB schemes compared to BE-Tree is between 19 to 31%. The improvement in search time compared to Siena is between 97 to 99% for the uniform tests. The results for the Zipf tests is comparable with respect to BE-Tree. The performance speedup of PUBSUB with respect to Siena is between 38 to 147 for the Zipf tests. The subscriptions in Zipf tests have a large number of common attributes, which results in deep trees for both PS-RBPST and PS-IT. The search performance of PUBSUB degrades as a results, since a large number of buckets are visited and the subscriptions stored in these buckets are all compared with the event.

The relative performance of the two PUBSUB schemes is comparable. The performance of PS-RBPST is slightly better than that of PS-IT especially when the number of subscriptions exceeded a million and the degree of overlap between subscriptions is high (as

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Figure 6: Parameters used with BEGen for generating datasets
in the Zipf tests).

![Search time with varying dataset size](image)

**Figure 8:** Search time with varying dataset size (microseconds/event)

4.3 How search time varies with the number of dimensions (or attributes) in the system

![Search time with varying number of dimensions](image)

**Figure 9:** Search time with varying number of dimensions (microseconds/event)

All of the pub/sub systems being studied display the same trend in search time as the number of attributes is increased. The search time decreased slightly with an increase in the number of dimensions. As the dimensions in a system are increased, the degree of overlap among subscriptions tend to decrease if the average number of attributes in subscriptions remain the same. This translates into the observed reduction in search times. On the tests based on uniform distribution, PUBSUB is faster than BE-Tree by 24 to 30%, while on the Zipf tests PUBSUB is 6.2 to 7.5% faster than BE-tree. BE-Tree is faster than Siena for the uniform and Zipf tests.

5. CONCLUSION

PUBSUB is a versatile, scalable, and efficient publish/subscribe system. Although the present implementation includes only 2 choices (interval tree, and red black priority search tree) for the data structure $D$ that is used to partition subscriptions based on the predicates of a single attribute, the set of available data structures for $D$ is readily extendable to include structures such as Aho-Corasick trees [17] and suffix trees [18] for string type attributes and operators. Our selection for the initial data structures was motivated by their suitability for predicates that specify a range of values.

We compared, experimentally, the performance of PUBSUB with that of BE-Tree [1] and Siena [2, 3] in an environment where event processing dominates subscription insert/delete. The same settings were used to generate our datasets as were used in [1]. Additionally, we used very large data sets containing over a million subscriptions. In general, there were two different types of datasets — those based on predicates selected from the attributes’ pool using uniform distribution, and those based on predicate selection using Zipf distribution. PUBSUB performed the best on the uniform tests, while on the Zipf tests, the performance of PUBSUB is comparable to BE-Tree. On our tests, the speedup, in event processing, of the fastest version of PUBSUB relative to Siena ranged from a low of 38 to a high of 330 and averaged 201 for the uniform and the Zipf tests. The speedup range relative to BE-Tree was between 1.23 to 1.48 and averaged 1.36 for the uniform tests and was comparable to BE-Tree on the Zipf tests.

It should be emphasized that although our experiments used the same data structure for all attribute structures, we expect that in real-world applications optimal performance will be achieved with a heterogeneous selection of data structures with interval trees being used in some attribute structures, red black priority search trees in others, and so on. The architecture of PUBSUB readily supports this heterogeneity.

6. REFERENCES


