Mobility support through caching in content-based publish/subscribe networks

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Abstract

In a publish/subscribe (pub/sub) network, message delivery is guaranteed for all connected subscribers at publish time. However, in a dynamic mobile scenario where users join and leave the network, it is important that content published at the time they are disconnected is still delivered when they reconnect from a different point. In this paper, we enhance the caching mechanisms in pub/sub networks to support client mobility. We build our mobility support with minor changes in the caching scheme while preserving the main principles of loose coupled and asynchronous communication of the pub/sub communication model. We also present a new proactive mechanism to reduce the overhead of duplicate responses. The evaluation of our proposed scheme is performed via simulations and testbed measurements and insights are given for future work.

1. Introduction

The publish/subscribe paradigm has become an important architectural style for designing distributed systems. Applications that exploit a pub/sub communication paradigm are organized as a collection of autonomous components (clients), which interact by publishing events (messages) and by subscribing to the classes of events they are interested in. The broker (or mediation router or rendezvous point) is responsible for collecting subscriptions and forwarding events to subscribers. In pub/sub networks the selection of a message is determined entirely by the client, which uses expressions (filters) that allow sophisticated matching on the event content.

There are several research efforts concerned with the development of an event notification service including IBM's Gryphon [1], Siena [2], Elvin [3], JEDI [4] and REDS [5] which implement the pub/sub architecture. Most of them address scalability and ease of implementation by realizing the broker tree as an overlay network.

In all the above pub/sub systems, any message is guaranteed to reach all interested destinations. This holds for all clients that their subscriptions are known to the network at publish time. However, there are cases where clients joins the network after the publication of an interesting message, or move around the network during their lifetime. In traditional pub/sub schemes it is not possible for a new subscriber to retrieve previously published messages that match his/her subscription. Therefore, enabling caching for retrieval of past information is one of the most challenging problems in content-based pub/sub networks.

The majority of the overlay pub/sub systems are designed not to tolerate any form of topological reconfiguration, therefore they cannot be exploited in those application scenarios where decoupling would be most beneficial. Here we are interested in supporting the mobility of clients, where a client is disconnecting from the network and reconnects from a different point later in time. Particularly, we will use our research on caching in pub/sub systems [6] to support mobile clients and we will examine the resulting trade-offs between caching efficiency, system overhead and message delivery guarantees to the mobile clients.

The rest of the paper is organized as follows. Section 2 discusses related work both in caching and mobility support in pub/sub systems. In section 3, a brief introduction of the pub/sub architecture is given, followed by the description of our already proposed caching scheme. In section 4 we present our approach to support mobility of clients while section 5 describes our proposed duplicate response dropping mechanisms. Moreover, sections 6 and 7 report on the performance evaluation of the proposed system through simulation and testbed measurements respectively. Finally, section 8 concludes our experience and discusses future work.

2. Related work

Caching as a mechanism for storing data in pub/sub systems has not received attention in the literature. In [6] we introduced a caching mechanism where brokers opportunistically caches information to make it available to future subscribers. We actually put forward a different aspect of caching, focusing on preserving the information over time instead of making information available in nearer space as the traditional caching schemes. Authors in [7] proposes a caching mechanism, for wireless ad-hoc networks based on buffers, that offers a way to integrate data repositories distributed in the network. Their approach concentrates on the class of applications that commence normal operation after having seen a sequence of events, while our approach is not confined in any particular class of applications, being more general in that way. Finally, in [8] and [9] authors propose a historic data retrieval pub/sub system where databases are connected to various brokers, each associated with a filter to store particular information. The work on those two papers is based on predefined caching points in the network and differs from our opportunistic point of view, where each broker of the network is a potential caching point for each published message.

The issue of mobility or relocation of clients in a pub/sub system has not been explored in great detail. The first pub/sub system that supported mobile clients was JEDI, where a client used two functions (*move-out* and *move-in*) to explicitly detach from the network and reconnect to it, possibly through a different broker. In [10] authors implement a mobility support service that is independent of the underlying pub/sub overlay and transparently manages active subscriptions and incoming messages when a client detaches from one broker until it reattaches at another. They use mobile service proxies which are independent, stationary components that run at the edges (where clients exist) of the pub/sub network. In other words they use a second overlay network to take care the mobility of the clients. That second overlay is responsible to gather the published events, that matches the interests of the mobile client, and deliver them when the client reconnects to the network. The proxies of that second overlay should be aware of the topology of the mobile service network, since they should directly contact each other when a client moves among them. Finally in [11] authors present COMAN (COntent-based routing for Mobile Ad-hoc Networks), a protocol to organize the nodes of a MANET in a tree-shaped network able to self repair to tolerate the frequent topological reconfigurations. COMAN was designed to minimize the number of brokers whose routing information are affected by topological changes, but it is not support the retrieval of lost messages after the reconfiguration of the network.

3 The pub/sub system with caches

3.1 The pub/sub architecture

We consider a pub/sub system that uses the subscription forwarding routing strategy [2]. The routing paths for the published messages are set by the subscriptions, which are propagated throughout the network so as to form a tree that connects the subscribers to all the brokers in the network.

Particularly, when a client issues a subscription, a `Subscribe()` message containing the corresponding subscription filter is sent to the broker the client is attached to. There, the filter is inserted in a Subscription Table (ST), together with the identifier of the subscriber. Then, the subscription is propagated by the broker, which now behaves as a subscriber with respect to the rest of the network, to all of its neighboring brokers. In turn, the neighboring brokers record the subscription and re-propagate it. This scheme is usually optimized by avoiding subscription forwarding of the same event pattern in the same direction exploiting "coverage" relations among filters.

3.2 Enabling caching in pub/sub systems

In this section, we give a short description of the caching scheme firstly introduced in [6]. In our system, each broker is selected as a candidate caching point for a message as long as it has in its subscription table at least one client subscribed in this message, and depending on the caching policy (the broker) caches or not each published message matching the subscriptions of its clients. In this paper, we call that cached message as "old" message/information. In order to retrieve the old information, we added to the system two additional types of messages, `Request()` and `Response()`. A client node interested in old content sends a `Request()` message with the interested filter. We used source routing for the forwarding of the `Request()` (the path is being built hop by hop and is included in the `Request()` header). A broker upon receiving the `Request()` message checks in its Subscription Table (ST) for subscriptions matching the requested filter. The subscription can be either from another broker or from a client. The broker forwards the `Request()` message to every existing subscribed broker. Each broker -recipient of a request message- with at least one matching client subscription, searches in its cache for messages matching the initial filter. If a matching is found, a `Response()` message is initiated.

As described in [6] a `Response()` message carries an old message as well as the sequence of nodes carried by the initiating `Request()` message (source routing). When a broker receives a `Response()` message, pops off its identifier from that sequence and forwards it to the first broker of the remaining sequence. In the end, the client will receive the message. With the above procedure, every client will receive every old message matching its filter and is still cached in at least one cache in the system. Figure 1 shows how client C is trying to retrieve old information matching his filter $fltr\_c$ (we suppose that $fltr\_c$ matches both filters

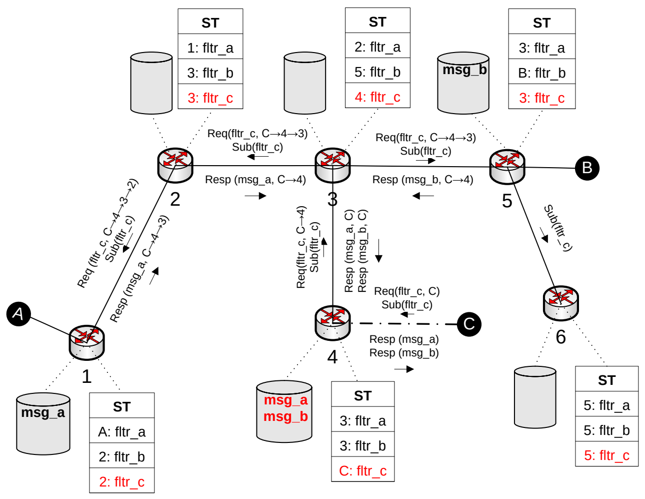

Figure 1. Caching and retrieving of old information (in red are the new entries after the appearance of client C).

$fltr\_a$ and $fltr\_b$).

In [6] a message is removed from a broker's cache when all the interested client subscribers have been unsubscribed, even if the cache is not full. This happens since future requests cannot reach that broker due to the lack of entries in the subscription tables of the rest of the brokers, pointing to that corresponding broker. Moreover, we used the first-in first-out (FIFO) with regenerations policy (similar to Least Recently Used) as a way to select the message to be dropped each time a cache is overflown. A Bloom-filter-based mechanism [12] could be used to solve scalability issues that might arise by the usage of source routing and the accumulation of broker ids at the header of the `Request()` and `Response()` messages, but such an analysis is out of the scope of this paper.

4. Mobility support

In this section, we describe a technique of using the already proposed caching scheme to provide support to mobile clients, like in [10], but using the same pub/sub overlay and without adding new functionality. Particularly, using a portion of each broker's cache, we allow brokers to manage subscriptions and publications on behalf of the mobile clients, both while they are disconnected and during the switch-over phase.

When the client is connected, publishes and receives messages directly to and from the pub/sub network. Before detaching, the client sends to the broker (call it broker 1 in figure 2), that he is attached to, a `Request()` message requesting to detach. That request message is similar to the message described in the above section but instead of the requesting filter it contains the "id" of the corresponding client. The broker has already in its Subscription Table "ST" the id of the client and its subscription filters and now whenever a message, matching those filters, arrive at the broker he directly caches it (apart from delivering it to the rest of the connected clients, if any, with a matching subscription). Until now the procedure is exactly the same with the procedure of the caching mechanism described above. The different is the treatment of those cached messages.

More specifically, the messages that match the subscription of the mobile client are never removed from the broker's cache (only if the whole cache is full) until the client retrieves them. In other words, the cache of the broker is divided in two parts. The first one (call it "*emergency cache*") is for the clients in "movement" while the second part is used for the traditional caching scheme. The size of those parts is not fixed, particularly when there is no client in movement the whole cache is used for the traditional caching scheme but when the broker serves mobile clients the cache is mainly used to support this mobility.

When the mobile client reconnects to the network, from a different broker (say broker 3), issues a `Request()` message with the subscription filter (or filters or part of them) that had subscribed to the pub/sub network before the movement and the "id" of the broker that was connected (broker 1 in the example of figure 2). That request message will reach according to [6] broker 1. Broker 1 upon receiving that request responds (using `Response()` messages) with the cached messages (messages that arrived when the client was in movement, msg_a_1 - msg_a_n in the example), unsubscribes the mobile client from its Subscription Table and releases the part of the cache that was devoted to that client. This means that those messages are treated according to the scheme in [6] and are removed from the cache if there are not any subscriptions in the broker from clients interested in those messages (like in figure 2) or the cache is full (FIFO with regenerations or any other cache placement/replacement algorithm [13]-[14]).

5 Handling multiple responses

While the proposed mobility support mechanism does not produce multiple duplicate responses, since only one broker responds to the mobile client's request, the caching and retrieving scheme has as side effect the possible production of multiple identical responses on a single request. To deal with this effect, we provide our system with two (reactive and proactive) duplicate preventing mechanisms. In the reactive mechanism, every broker with at least one client subscriber, upon the arrival of each response message, checks whether the message already appears in its cache and in case this is true, drops the response message. Oth-

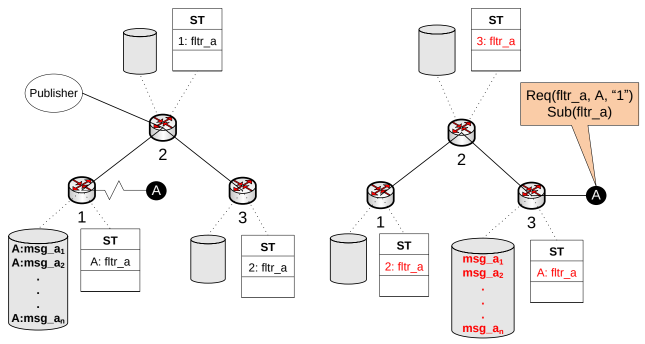

Figure 2. Mobility support mechanism. When client A is in movement messages msg_a_1 - msg_a_n appeared in the network.

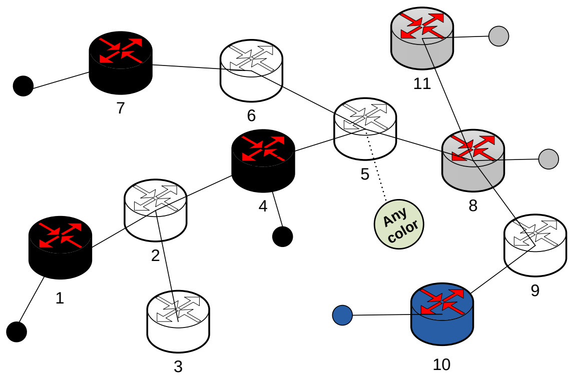

Figure 3. A dispatching network where the color of each broker represents the content of the cached messages and the their client subscription filters.

erwise, it forwards the message according to the technique described in section 3.2. The reason for searching the cache of every broker upon the arrival of each response, is because responses follow the same route (backwards) as the requests. This means that the request for initiating the response has also been processed by the broker under question which may have responded to that request with the same message(s). Note also, that the requests cannot be dropped in a similar manner, because we consider a content-based network, and finding a matching message in a proximity broker does not guarantee that there is no other different message in the network matching the same subscription.

In the proactive counterpart, every broker with a cached matching message, apart from responding to the `Request()` message, before forwarding it to its neighboring brokers appends to the `Request()` header the "*id*" of the responded message. The brokers -recipients of that request message- will only respond with messages matching the requested filter and their ids are not in the `Request()` message, since those messages have already been sent to the client issued that `Request()`.

In the example of figure 3, we suppose that brokers 1, 4, and 7 have in their cache the same "black" message while brokers 8 and 11 have in their cache the same "grey" message and broker 10 has in its cache a "blue" message. If now a client connects to broker 5 and requests with some filter matching "any color", the request will reach all the above mentioned brokers. Brokers 4 and 7 will reply with a response message but the response message sent by broker 7 will be dropped upon reaching broker 5 given that broker 5 has already cached the "black" message, after the reception of the response initiated on broker 4 (reactive mechanism). Broker 1 won't respond since the "black" message cached is the same with the one cached in broker 4 and the "message id" is carried by the `Request()` message (proactive mechanism). Similarly according to the proactive dropping mechanism only the response of broker 8 will be delivered to the client. Finally, the response initiated in broker 10 will also reach the client. With this simple example is obvious how important are those two duplicate dropping mechanisms and especially the proactive one. The disadvantage of the proactive mechanism is the usage and the accumulation in the request's header of the "message ids" cached in the network which is not scalable, but which can be beneficiary in a well defined environment where the total number of the published messages could be limited or finite.

6. Performance evaluation

In this section, we evaluate the proposed mechanism using a discrete event simulator. $N = 7$ brokers are organized in a balanced binary tree and clients are dynamically generated on each broker according to a birth and death process with birth rate λ_c and death rate μ_c. Those clients with rate λ_mob go mobile and reconnect to the network after a randomly selected period of time (with mean value Δt). New publications occur to the network with rate λ_{msg}. Each broker has a cache capable of storing k messages. We are looking at the following interesting metrics.

- The *absorption time* of a message m is the time passed from the publication of m until it gets disappeared from the network. This metric is indicative of the capability of the network to maintain messages in its memory.

- The *responses per request* is measured for each successfully responded request and corresponds to the number of total responses that the system would have generated if no duplicate dropping mechanism was used. This metric is representative of the replication and the overhead in the network.

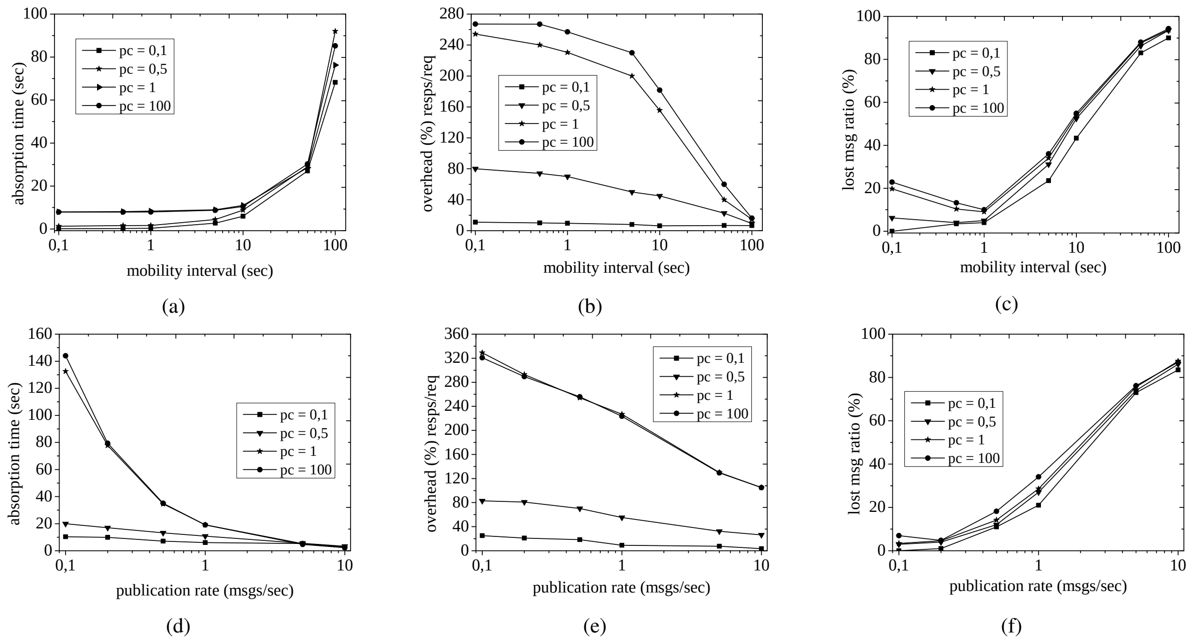

Figure 4. Performance of the mobility support mechanism for several values of the mobile time interval Δt (upper graphs) and the publication rate λ_{msg} (lower graphs).

- The *lost message ratio* is measured for each mobile client and is the ratio between the publications that matches his subscription and were published when he was disconnected and the messages that are finally delivered to the client after his reconnection to the network. This metric is indicative of the capability of the network to support mobile clients and is indicative of the contention in the caches when they support mobile clients.

The above metrics are random variables and we estimate their mean by simulating thousands of observations. We set two experiments, one varying the time interval that the client is mobile (Δt) and one varying the publication rate λ_{msg}. Those two sets are similar to varying the dynamics of the mobile clients (rate of going mobile and rate of reconnected to the network) and varying the cache size respectively. We run those two sets with four different values of the client dynamics $\lambda_c/\mu_c = \rho_c = 0.1, 0.5, 1, 100$ which is similar to varying the number of the brokers in the system.

Figure 4 shows three pairs of graphs. In the first pair (subfigures "a" and "d"), we can identify the exponential nature of absorption time. Particularly, increasing the time interval that a client is mobile increases the mean absorption time of messages since now more messages are cached in the "emergency cache" and stay there for more time. But increasing the number of publications (publication rate) has as effect the contention of messages in the emergency cache (more messages now have to be cached). The same effect of message contention in caches occurs and in the case of increasing the mobile time interval.

In the second pair (subfigures "b" and "e"), we present the gain in overhead (percentage) as (duplicate) responses per request that we have in our system by the usage of the two duplicate dropping mechanisms compared to the case that we have no dropping duplicate mechanisms. Using those two dropping mechanisms, we have only one response per successful request. For low mobility time intervals, we have a gain of more than 250% something that also occurs in low publication rates (350% gain). In high mobility time intervals and publication rates that gain is less since now due to contention in caches we have less duplicate messages stored at each cache meaning less duplicate responses per successful request. In low values of the client dynamics, that gain is also low since now clients remain "alive" for less time in the system and messages are not stored based on the technique described in section 3.2. This overhead gain increases with the number of nodes in the network.

Finally, in the last pair (subfigures "c" and "f")we present the lost message ratio described above. It is obvious that higher mobility time intervals or publication rates forces the "emergency cache" to store more and more messages squeezing its capability to retain all the messages due to contention increasing in that way the lost ratio.

7. System design and experimentation

We implementated the proposed system on top of REDS [5]. Apart from the modifications made and presented in [6] for the purposes of this paper, we altered the logic in caching to support the mechanisms described in 4 and 5. We used 5 laptops equipped with a 1,6 GHz Intel Celeron M CPU, 512 MB of RAM. The 3 computers were connected via Ethernet switch to set the pub/sub overlay network as shown in figure 2. Another computer played the role of a stationary publisher client while the final laptop played the role of a mobile subscriber client. In our testbed experiments, the mobile client issues one subscription while the publisher publishes a series of publications (all publications matches that subscription) at a constant rate of λ_p publications per second ($\lambda_p = 1, 2$) and publishes for 50 seconds (50 and 100 messages accordingly). The mobile client migrates from one broker to another only once and remains disconnected for a fixed interval of $\Delta t = 15$ seconds.

Figure 5 shows two pairs of graphs that we call *message/delivery time traces*. The "message" axis is the number of messages delivered to the mobile client, while the delivery time is when the message is received by him (set time to zero when the first message is delivered). The left-side graph shows the case where no mobility is supported, while the right one shows the effect of our mobility support mechanism. Every point in the graphs corresponds to a message received by the client either through the publish or the request process. The part of the graphs where there is no message delivery represents the time interval that the client is disconnected from the overlay network, while the vertical part of delivered messages (right-side graphs) after the reconnection of the client represents the responses delivered to the client to his request sent to the broker that was attached before the movement. It is obvious that all the published messages finally arrive to the client while there is no delay due to the processing associated with relocation.

8. Conclusion And Future Work

In summary, we have extended our proposed caching scheme to support mobility of clients and we presented a new duplicate dropping mechanism to reduce the system overhead. Evaluation via simulations and testbed measurements presented the performance of the system regarding information survivability, overhead and quality of the proposed mobility support scheme. This work can be extended in many ways, from deriving applications to extensions in mobile ad-hoc networks where both brokers and clients are free to move.

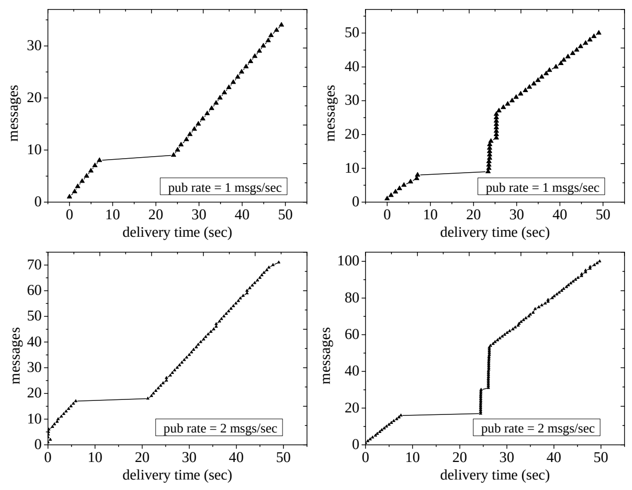

Figure 5. No mobility support (left-side), mobility support (right side).

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