I Know What You Did Last Summer: Time-Aware Publish/Subscribe for Networks of Mobile Devices

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Abstract

Smart mobile devices are increasingly ubiquitous and are the primary source of user-generated content, and current communication infrastructures are failing in keeping up with the rising demand for the avid sharing of such content. To alleviate this problem and fully harness the amount of resources currently available at the network edge, mobile edge paradigms started to emerge. Though, application developers still struggle to tap that potential at the edge due to the lack of adequate communication and interaction abstractions. Thus, we propose a high-level abstraction that can be easily exploited by developers to design mobile edge applications focused on data dissemination. In this paper, we propose THYME, a novel extended topic-based, time-aware publish/subscribe system for networks of mobile devices. In THYME, time is a first order dimension. Each subscription has an associated time frame, starting and ending either in the future, present, or past. Making the past available requires both subscriptions and publications to be persistently stored. We present the design of THYME and evaluate it using simulation, discussing and characterizing the scenarios best suited for its use.

1 Introduction

Smart mobile devices, like smartphones and tablets, are increasingly ubiquitous, and their increasing capabilities are turning them into pocket-size personal computers. The aggregate capacity of these mobile devices presents itself as massive computing and storage resource pools that are still highly under-exploited [5].

The pervasiveness of mobile devices makes them the primary tool for generating and sharing all sorts of content [5], and users expect to use such devices continuously to both access and share content like video or photos [18]. This usage pattern places a huge burden on network infrastructures and cloud-based services alike, because they have to accommodate high loads to support continuous user activity, namely in sharing user-generated content, e.g., in social gatherings such as sports events or music concerts [6][8].

The typical alternative to sustain such high demand is to set up special communication infrastructures just for those events [33]. Unfortunately, in some scenarios (e.g., one-time events) it
might be logistically or financially nonviable to deploy such infrastructures [30]. In others (e.g.,
natural disasters, inhospitable locations), infrastructures might not even exist or be impossible to
set up [15].

To tackle such daunting scenarios and to fully exploit the amount of resources that are now
available at the network edge, novel computational paradigms, such as mobile edge computing [14]
and mobile edge cloud [6], have emerged. Though, it is still challenging for application developers
to easily tap this potential, namely due to the lack of adequate communication and interaction
abstractions.

Recent research [16, 22, 31, 32] is leveraging on device-to-device (D2D) communication to provide
peer-to-peer ad-hoc communication among mobile devices at the network edge. These D2D
mechanisms can complement and work side-by-side with typical communication infrastructures [26].
However, they still lack adequate abstractions for developers, forcing them to reason and address
many issues that are related with the mobile and wireless nature of the execution environment,
which is not only hard and time-consuming, but also error-prone.

In this work, we aim at providing a high-level abstraction that can be readily exploited by
developers to design “mobile edge” applications focused on the dissemination of data among nearby
mobile devices. For that purpose, we focus on the publish/subscribe (P/S) paradigm. This simple
communication abstraction provides full decoupling in time, space, and synchronization between
publishers and subscribers [9], which facilitates loosely coupled, spontaneous interactions (required
for this kind of dynamic and pervasive edge environments).

In this paper, we propose Thyme, a novel extended topic-based, time-aware publish/subscribe
(T-P/S) system for wireless networks of mobile devices, working as a data dissemination/storage
service at the network edge. The extended topic-based feature stems from the fact that Thyme’s
subscriptions support arbitrary propositional logic formulas (using topics as literals), whereas
typical topic-based systems only allow one topic per subscription.

In the scenarios we are addressing (e.g., sports games), individual moments are intrinsically
tied by time relations (e.g., the goal in the first half of the football game). Also, when consuming
contents, users are often interested in events that have these associated time references (e.g., find
pictures of the goalkeeper’s save in the second half of the game). Accordingly, Thyme considers
time to be a first order dimension and we define it as a T-P/S system, whose data is persistently
stored, and where subscriptions include a time frame that define its active time-span, either in
the future, in the present, or in the past. As a result, the target publication space is confined to
publications that happen(ed) within the specified time frame, which effectively provides the full
time decoupling of the P/S paradigm. To the best of our knowledge, Thyme is the first system
to expose, in this context, a P/S interface with support for subscriptions within a time scope that
can reside in the past.

We present two different materializations of Thyme. The first one, Thyme-PL/SG, is a
simplistic approach using flooding. The second more intricate one, Thyme-DCS, is inspired by
the fact that geographical positions have a close relation to topology in wireless networks, and
follows a data-centric storage (DCS) approach using a geographic hash table (GHT) as a storage
substrate.

In summary, the contributions of this paper are the following: i) the concept of a P/S system
with intrinsic time-awareness, requiring persistent subscriptions and publications ([2]); ii) the
design of Thyme, a novel extended topic-based T-P/S system ([3] and our two materializations
of this proposal ([4] and [5]); and iii) the characterization of the scenarios best suited for the use
of the proposed solutions, using simulation ([6]).

2 Time-Aware Publish/Subscribe

This time-awareness concept stems from the facts that each publication is timestamped, and each
subscription is active within a specific time frame. Thus, even if a subscription’s time frame lays
partially or entirely in the past, the subscriber will still be notified about (past) publications
contained within that time frame.
A T-P/S system offers the usual operations of a regular P/S system, namely publish data, subscribe to topics, cancel a subscription, and retrieve previously published data. To support subscriptions with a time span in the past, published data must be persistently stored within the system. Accordingly, the T-P/S interface also supplies an operation to unpublish data, deleting it from storage.

2.1 Publishing Data

A data object is the basic unit of work and is seen as an opaque set of bytes. Every object has some associated metadata that consists in a tuple

\[ \langle \text{id}_\text{obj}, T, s, t_\text{pub}, \text{id}_\text{owner} \rangle \]

where: \( \text{id}_\text{obj} \) is the object’s identifier; \( T \) is a set of tags or keywords related to the object, e.g., hashtags used in social networks; \( s \) is a summary of the object, e.g., a thumbnail of an image; \( t_\text{pub} \) is the object’s publication timestamp; and \( \text{id}_\text{owner} \) is the publisher’s node identifier.

The system-wide unique object key is composed of the object’s identifier and the publisher’s node identifier, i.e., it is in fact a pair \( \langle \text{id}_\text{obj}, \text{id}_\text{owner} \rangle \). This enables different nodes to publish objects under the same identifier, turning the object’s identifier into a sort of a domain key, hence avoiding name collisions among nodes.

Tags are used as topics for subscriptions. Tagging is a flexible annotation scheme, e.g., by adding the publisher’s node identifier to the tags of its published objects, an application can easily enable the retrieval of all the objects published by a certain node/user.

2.2 Removing Data

The unpublish operation revokes a published object, making it inaccessible to future subscriptions. Note that a subscription targeting the past will not see unpublished objects, even if these were initially available in the subscription’s time frame.

2.3 Subscribing

With time as a first order dimension, a subscription consists in a tuple

\[ \langle \text{id}_\text{sub}, q, t_\text{s}, t_\text{e}, \text{id}_\text{owner} \rangle \]

where: \( \text{id}_\text{sub} \) is the subscription’s identifier; \( q \) denotes the query that defines which tags are relevant to the subscription; \( t_\text{s} \) is the timestamp defining when the subscription’s time frame starts; \( t_\text{e} \) is the timestamp defining when the subscription expires; and \( \text{id}_\text{owner} \) is the subscriber’s node identifier.

The query is a formula in propositional logic where literals are tags associated with published objects (e.g., ‘A & (B | C)’ captures objects tagged with A and at least one of B or C).

The \( t_\text{s} \) and \( t_\text{e} \) timestamps specify the time frame in which the subscription is valid, where the special value \( \perp \) represents, respectively, the times at which the system started and stopped to exist.

This allows the subscriber to specify any time frame that might be relevant to the subscription. For instance, assuming a subscription is submitted at time \( t \); \( t_\text{s} = \perp \) and \( t_\text{e} = t \) refers to events that happened before the subscription; \( t_\text{s} = t \) and \( t_\text{e} = \perp \) refers to events after or concurrent with the subscription; and \( t_\text{s} = t_\text{e} = \perp \) refers to events that occurred at any time. Notice that these parameters can also take concrete timestamp values.

Regarding notifications, there are two situations that can trigger the notification of subscribers: upon a publication, the detection that the object being published matches existent subscriptions; and upon receiving a subscription that spans into the past, the detection that previously published objects match this new subscription. In both cases notifications are sent to the respective nodes carrying the metadata of the matching objects. The objects’ metadata is the only information given to the subscribers for them to decide if objects are relevant enough for retrieval.
The unsubscribe operation revokes a subscription before it naturally expires after its end timestamp, \( t_{se} \).

### 2.4 Retrieving Data

Received notifications must be acted upon, and may either be discarded, trigger an immediate download, or be stored by the application and acted upon later.

In order to retrieve some published object, the retriever needs to know where to get that specific object from. This is a classical resource discovery problem. In Thyme, the minimum amount of information needed to get an object is its key (the pair \( \langle id_{obj}, id_{owner} \rangle \)).

### 3 The Many Leaves of Thyme

Now, we present a general overview of Thyme’s design, providing a time-aware publish/subscribe (T-P/S) interface.

#### 3.1 Use Cases

As a publish/subscribe (P/S) system, Thyme provides a generic data dissemination service. We argue that Thyme fits perfectly in scenarios where crowds are gathered, using their mobile devices to collect data (e.g., photos, video, text) and share it with people in their vicinity, akin to social networks [25].

Consider, for instance, a scenario where spectators in different parts of a football stadium may share their views of the game through self-generated (multimedia) content. In this case, spectators would be able to see key moments of the game from multiple viewpoints, including those of the spectators in key locations or closer to the field.

This kind of augmented user experience is already being explored using venues’ fixed communication infrastructures [34], which may be subjected to overload conditions and failures (e.g., power outages [8]). In turn, the mobile edge paradigms and the advances in device-to-device (D2D) communication offer the possibility to provide such enriched user experience with a negligible cost for infrastructure managers, while at the same time working to alleviate the load on those infrastructures.

#### 3.2 System Model

We consider a classical asynchronous model comprised of \( \Pi = \{n_1, \ldots, n_k\} \) nodes, with no mobility restrictions, other than those imposed by the venue they are in, and the natural speed limits of humans. We do not assume any specific radio technology. Nodes communicate by exchanging messages through a wireless medium (e.g., Bluetooth, Wi-Fi ad-hoc, Wi-Fi Direct), and have no access to any form of shared memory. Nonetheless, nodes should be able to establish communication channels with (all) their one-hop neighbors. We also consider the classical crash-stop failure model, whereby nodes can fail by crashing but do not behave maliciously.

Published object data is considered immutable. We do not consider security or access control concerns thus, only publicly sharable data is published (e.g., as in social networks). Due to the unreliable nature of wireless communication mediums, Thyme notifies subscribers of all relevant published data as completely and faithfully as possible, i.e., missing some notifications is permitted because applications are not expected to be mission-critical.

Each node has a globally unique identifier and can determine its geographical position, either through GPS or other means [19]. Thus, nodes can be aware if they are moving or stationary. We also assume nodes’ clocks to be synchronized (with a negligible skew). Both these assumptions are reasonable since we target mobile devices (e.g., smartphones) and nowadays, even low-end devices come equipped with GPS and synchronize their clocks with the network providers, while other solutions allow to effectively locate a user device even indoor (for instance through the monitoring of visible access points).
3.3 Architecture

In Thyme, akin to (flat) peer-to-peer (P2P) systems, nodes are functionally symmetric, sharing the same responsibilities and having no particular roles. There are no centralized or specialized components (like P2P super-peers or P/S brokers), and each node can be a publisher, a subscriber, or both.

Thyme’s design comprises three main layers, depicted in Figure 1. The bottom layer handles message routing. The middle layer addresses Thyme’s time-awareness, which requires both subscriptions and publications to be persistent. Such requirement is handled by the middle, storage layer. The top layer is Thyme itself, providing the T-P/S interface for applications.

As illustrated in Figure 1, we present two materializations for the two bottom layers (routing and storage): 1) one version uses a publish locally/subscribe globally (PL/SG) approach, where (un)publish operations are executed locally and (un)subscribe operations are flooded to every node in the system (see §4); 2) the other version follows a more intricate data-centric storage (DCS) approach using a geographic hash table (GHT) for storage (see §5).

3.3.1 Routing

In version 1 (PL/SG), the routing layer provides flooding to the entire network (using unreliable UDP broadcast), and (multi-hop) unicast using a typical ad-hoc routing protocol (e.g., DSDV, OLSR). In version 2 (DCS), the routing layer is materialized as a cluster-based GHT for wireless networks. Thus, the routing infrastructure is based on the notion of clusters or virtual nodes. Physical space is divided into a grid, i.e., equally-sized square-shaped cells, and all physical nodes within the geographic boundaries of a cell collaboratively act as a virtual node. Messages are addressed to geographic locations, thus routed to the cell that contains the location of the message destination. Messages addressed to a virtual node, i.e., a cell, are delivered to all physical nodes that materialize the virtual node managing the cell (in a similar way to [12]).

Wireless communication mediums are known to be subject to many forms of interference; hence some messages may be lost and not reach their final destinations. However, as a design principle in both versions, we do not provide any mechanisms to recover from lost messages on the wireless medium, delegating this responsibility to the upper layers (abiding by the end-to-end argument [23]).

3.3.2 Storage

Since subscriptions can target the past, publications have to be kept persistent in the system. So, Thyme’s architecture conceptually fuses a P/S system with a storage system.

In the PL/SG approach, each node stores its publications locally, while subscriptions are fully replicated in every node of the system. In the DCS approach, the use of the underlying GHT is two-fold: 1) virtual nodes (i.e., cells) are used to store published content and subscriptions; and 2) routing is exploited to match subscriptions and publications, i.e., cells act as virtual P/S brokers.
4 Thyme-PL/SG

This materialization of THYME employs a simple PL/SG approach (version 1). Publish and unpublish operations are entirely executed locally. Thus, publications are only stored (locally) by their owners.

On the other hand, subscribe and unsubscribe operations are flooded and executed in every node of the system. Hence, subscriptions are stored by every node, i.e., fully replicated. Notifications are triggered in two situations: upon a publication, the publisher node checks if the object being published matches any of the subscriptions it has stored; and upon a subscription (when flooding the respective message), each node that receives the subscription message checks if that new subscription matches any of the node’s previously published objects.

Download operations request the desired objects directly from the object owners, using the publishers’ node identifiers contained in the objects’ metadata received in the notifications. Here, the multi-hop unicast provided by the routing layer is used to contact the object owners directly. To recover from lost messages on the wireless medium, this operation uses a retransmission mechanism. After a configured amount of time has passed without receiving a reply, the operation is retried. If the (configured) maximum number of retries is reached, the operations fails with a timeout error code.

In this version, node mobility is handled in a completely transparent way by the protocol used in the routing layer.

Since publications are only stored locally by the object owners, this materialization does not guarantee the persistence of publications once the publisher node fails.

For a node to join the system, it first broadcasts a join request. To avoid replies from all the nodes that received the join request, only some (randomly selected) nodes will respond with all the subscriptions they have locally stored. The replies are also delayed a random amount of time (in a configured interval) to avoid message collisions in the wireless medium. This join procedure also uses a retransmission mechanism, similar to the download operation. If the maximum number of retries is reached, the joining node assumes it is alone in the network, and starts working as normal.

5 Thyme-DCS

In this version, THYME is materialized on top of a cluster-based geographic routing layer (version 2). It follows a DCS approach making use of the underlying GHT to provide a storage substrate. This approach has two complementary aspects: 1) it provides topology-awareness by design; and 2) it allows the inference of the location of relevant data to subscriptions, enabling access to such data using a location-aware strategy. This materialization leverages heavily on the notion of cell (or virtual node) conveyed by its routing layer.

5.1 Publishing Data

When executing a publish operation, this approach leverages on the cells conveyed by the underlying GHT and it indexes the object metadata by its tags \( T \), i.e., the cells resultant from hashing each tag in \( T \) store the metadata. The actual object is only stored in the publisher node and its current cell (see §5.2). This ensures only the object’s metadata is sent through the network.

Figure 2 illustrates the publication of a photo with identifier “beach.jpg”, and tags “beach” and “summer”. The cells resultant from hashing each tag are responsible for managing the object’s metadata and checking if subscriptions match this publication.

5.2 Replication

Since we target dynamic and pervasive edge environments, in order to provide data availability and tolerance to churn, this materialization provides two replication mechanisms.
Figure 2: Publish and subscribe operations. The tags’ hashing determines the cells responsible for managing the object metadata (cells 2 and 5) and the subscription (cells 2 and 13). If a subscription has overlapping tags with a publication (and vice versa) it will also have overlapping (responsible) cells, guaranteeing the matching and sending of notifications to the subscriber.

5.2.1 Active Replication

It takes advantage of the virtual nodes provided by the cluster-based GHT. Upon publishing, an object is disseminated inside the publisher’s cell. Onwards, every node inside the cell should be able to reply to download requests for that object. This ensures tolerance to churn and guarantees that published content will remain in the system even if publishers leave.

5.2.2 Passive Replication

It leverages on the nodes that already downloaded an object to provide more replicas of that same object scattered in the network, increasing data availability. At the same time, it offers a list of multiple locations from where the object may be downloaded.

5.2.3 Replication List

To take advantage of both these replication mechanisms, the system needs to keep track of the whereabouts of each object replica. This bookkeeping is done by listing an object’s replicas location in its metadata, in what we call replication lists, $L_{rep}$ (a list of pairs $\langle id_{node}, cell_{node} \rangle$). Thus, in this case, the object metadata consists of a tuple $\langle id_{obj}, T, s, ts^{pub}, id_{owner}, L_{rep} \rangle$.

Since nodes can move, their location may change over time. Hence, after a node stabilizes in a (new) cell, it must update its location for the passive replicas of the objects it holds.

5.3 Removing Data

In the unpublish operation, the object metadata indexed by the object’s tags is removed from the responsible cells. However, while the active replicas are also explicitly removed, the same does not happen to the passive ones.

5.4 Subscribing

Subscriptions are extended with the location of the subscriber node, $cell_{owner}$. Thus, a subscription consists of a tuple

$\langle id_{sub}, q, ts^{s}, ts^{s}, id_{owner}, cell_{owner} \rangle$.

The subscriber’s cell address is required because the geographic routing layer only routes messages to geographical positions. Hence, there is the need to know the cell where to send notifications to. This information needs to be updated every time the subscriber node changes its cell.

5.4.1 Divide and Conquer

Here, we leverage on the fact that every propositional logic formula has an equivalent in disjunctive normal form (DNF). Thus, we employ a divide and conquer strategy of breaking the disjunction into its individual conjunctive clauses, and evaluate each one separately. For a match to occur, it
suffices that one of the conjunctions evaluates to true. The use of DNF enables load balancing when checking for a match between a publication and a subscription, since the work of verifying a match can be split among different cells/nodes, each evaluating only one of the query’s conjunctions. Additionally, it minimizes the amount of information transmitted to the responsible cells, since each subscription message only needs to carry the respective conjunction.

For each conjunction, we select a random non-negated literal as its key. The result of hashing that literal determines the cell where to send that part of the query. That cell becomes a (virtual) broker for the subscription, and the nodes in the cell are responsible for checking for publications matching the subscription, and notifying the subscriber if need be. Figure 2 depicts a subscription of a query with two conjunctions. For each, one of its (non-negated) literals is chosen as its key, and determine the cells that will become the virtual brokers for the subscription.

5.4.2 Notifications

Upon a publication, the cells indexing the object metadata by its tags are responsible for checking if the publication being indexed matches any existent subscriptions stored locally. Upon a subscription, the cells indexing the subscription by its keys are responsible for checking if the locally stored objects match the new subscription.

5.4.3 Excess of Past Notifications

When issuing a subscription for some time in the past, and for a tag with many previously published objects, the subscriber will be flooded by a large amount of notifications. Besides flooding the subscriber with lots of notifications, this also implies lots of communication.

To attenuate this problem, when subscribing for some time in the past, the subscriber is only notified about $n$ matching objects from a total of $x$ objects. Then, if interested, the subscriber can request more matching objects. Receiving the notifications in expressly requested batches. All the subsequent publications matching the subscription will be notified as usual.

5.4.4 Moving Subscribers

When a subscriber moves to a different cell, it must update its location for every active subscription it owns. Notifications sent to subscribers on the move may never reach their destination. In such cases, the underlying routing layer returns negative acknowledgements (NACKs) (see §5.8.4) for messages addressed to individual nodes that could not be delivered. NACKs are used to convey that a node is no longer in its supposed cell, which may be caused by movement or node failure. Node movement will be detected through the subscriber’s location update. In such case, we can re-send the notifications that were not previously delivered. Otherwise, we can simply stop sending notifications.

5.4.5 Unsubscribing

For each subscription, the subscriber keeps the list of subscription keys. When executing an unsubscribe operation, unsubscribe messages are sent to the cells determined by the hashing of each key.

5.5 Retrieving Data

Download operations leverage the replication mechanisms in order to have multiple locations from where to retrieve an object. From all the locations in the replication list, the node chooses the closest one to itself, and sends a download request for the desired object. If a negative reply is received, the requester proceeds and tries to download the object from the next location in the replication list (until no more options are available, or a maximum number of retries is reached). In case the last retry is reached, it will always try to download the object from the cell actively
replicating it (if it was not already tried), because it offers higher chances of success comparing to every other replica.

The use of geographical routing makes it easier for nodes to make hints on which “download locations” are better (i.e., closer). The geographical approach makes possible to use a more concrete metric for distance in the network than the number of hops. This approach reduces the distance data has to travel in the network, when retrieving an object.

5.6 Per Operation Retransmission Mechanism

Similarly to the first materialization of Thyme (§), to address the problem of collisions and interferences on the wireless medium, this materialization also employs a per operation retransmission mechanism (for all the five Thyme operations). In this materialization, one operation may result in the sending of multiple messages to different cells (e.g., publishing an object with two tags, as in Figure 2 results in sending publish messages to two different cells). Thus, after a configured amount of time without receiving the expected replies (one from each cell), the message is retransmitted (until a configured maximum number of retries), but only for the cells that did not send a reply back.

5.7 Joining the System

Instead of sending a broadcast, like the PL/SG version, in this materialization, a node joining the system waits a configurable amount of time, listening for the periodic beacons sent by all nodes. During that waiting time, if the node listens to some beacon sent by another node in its cell, the sender of that beacon is used as the entry point to the system, and exchange a join request and respective reply (with all the cell state).

This join procedure also uses a retransmission mechanism. After sending a join request, if a reply is not received within a configurable amount of time, the joining node starts another round of waiting for the periodic beacons. If the maximum number of retries is reached, it assumes it is alone in the cell, and starts working as normal.

5.8 Cluster-Based Geographic Routing

In a geographical distributed hash table, nodes know their positions and keys are hashed into that same domain. The node responsible for a key is the one closest to the key’s geographical position.

Inspired by works from both wired [12, 17] and wireless [1, 24] settings, we adopt a cluster-based approach. This approach conveys the notion of virtual nodes or cells. Space is divided into a grid (like in Figure 2) and all nodes inside each cell act collaboratively as one.

5.8.1 Routing

Our routing scheme is very similar to the ones used in [1, 20]. Routing is done on top of these virtual nodes, i.e., at cell-level, using a geographic routing protocol—a variation of the greedy perimeter stateless routing (GPSR) protocol [10]. GPSR makes greedy routing decisions, forwarding messages to the next neighbor geographically closer to the message destination. When such strategy is not possible, the algorithm resorts to a recovery mode that forwards messages around the voids in the network. For forwarding messages from cell to cell, we use unicast in order to take advantage of the (per hop) MAC-level retransmission mechanism.

The interface exposed by this routing layer provides operations to route messages to an individual node (within a specific cell) and to broadcast messages within the context of a single cell, besides providing a routing mechanism between cells.

The one-hop broadcast is used as a neighbor discovery service (transmitting periodic beacons with the node’s current cell), and as the intra-cell communication primitive. Since broadcasts are not acknowledged at the MAC-level, they are more likely to fail, which makes it a best-effort communication primitive.
5.8.2 Dynamic Cell Population

Since it is impossible to ensure every cell has at least one node, some keys may be left without
nodes to manage them, i.e., cells may be empty. We address this in the same way as [1][20], forcing
keys to take an entire loop around the empty cells, stopping in the cell closest to the supposed
destination (which becomes a proxy of the key’s destination cell).

This raises another problem when nodes populate previously empty cells, or leave the system
and make some cell empty. A cell leaving the network delivers all its keys to its proxy cell. An
entering cell needs to receive its keys from its proxy cell, and also all the keys of empty cells for
which it act as a proxy.

5.8.3 Mobility

Concerning mobility, we argue that moving nodes render routing information volatile. Thus,
only nodes that are stationary actively participate in the routing of messages. Since our target
scenarios have mild mobility patterns (i.e., nodes do not move constantly, and some might not
even move during the entire event), only stationary nodes form the GHT. When a node starts
to move, and leaves its current cell, it stops participating in the routing protocol (i.e., it stops
forwarding messages). It resumes the protocol when it detects itself as being stationary, by joining
the local cell. While moving, nodes still process received periodic beacons, allowing them to keep
communicating with the GHT.

5.8.4 Negative Acknowledgements

Nodes are not individually addressable, but by knowing its current cell, a message can be sent to
a node in that specific cell. To allow the upper layers to react to a node’s failure or migration
from one cell to another, the routing layer replies with a NACK to a message source node, when
a message addressed to an individual node could not be delivered.

5.8.5 Cell-by-Cell Destination Aggregation

For messages that are to be delivered to multiple destinations (e.g., notifications), we optimized
our routing scheme by only propagating a single message to those destination. This message is
only duplicated when strictly required, which happens when the message’s next hop for different
destinations is not the same. This contributes to reduce energy consumption and the occupancy
of the wireless medium.

6 Evaluation

Our evaluation seeks to answer the following questions:

- Which are the trade-offs provided by each version of THYME?
- How does each materialization deals with churn?
- How do they react to node mobility?

Each data point reports the average of 5 randomly generated network topologies, each indepen-
dently run 3 times, making a total of 15 runs per data point.

6.1 Implementation

A meaningful real world evaluation would require a significant number of mobile devices. Not
having access to such infrastructure, we resort to simulation and implement both materializations
of THYME in the ns-3 network simulator [21]. We use ns-3.27 and nodes communicate through
WiFi ad-hoc (using UDP). The PL/SG version uses DSDV as the routing protocol.
In the DCS version of Thyme, when a cell becomes empty (i.e., when all nodes leave a cell), all the data stored in it needs to be transferred to another cell. The reverse happens when an empty cell becomes populated (§5.8.2). Currently, we do not implement such mechanism thus, in our experiments, cell population is static (i.e., populated and empty cells will remain as such throughout the system’s lifetime). This poses some limitations regarding node mobility and churn in the DCS version. A node cannot leave its cell if it is the only one in it (but it can still move inside its cell). Also, nodes can only move among populated cells.

6.2 Simulator Setup and Traces

Unless stated otherwise, all non-mentioned parameters were left with the simulator’s default values. We used Wi-Fi 802.11g configured with a constant rate manager and a data rate of 6 Mbps. The RTS/CTS threshold was 1500 bytes.

In order to mimic a realistic scenario, we emulate an application similar to an online social network on top of Thyme, and we use tweets as user publications. We generate operation trace files with the scenarios behaviors, i.e., all the operations to be issued.

We crawled the tweets issued during the 2016 UEFA European Championship final between Portugal and France. The tweets were used as user publications, where: the tweet id was used as the object identifier; the text was used as the object’s data; the tweet timestamp was used as the object publication time; and the hashtags were used as the object’s tags. For the traces’ generation, the top-k most active users were chosen, and every other operations were generated from that, using exponential distributions configured with different λ values (i.e., rates). Subscriptions were generated taking into account the tags of the published objects, and the top 60 % of the most popular tags were for the subscriptions’ queries (for simplicity, each subscription subscribed to only one tag chosen at random). Subscriptions were generated in two forms: in the past (with \( t_s^p = t_s^f = \perp \)) and in the future (with \( t_s^p = \text{now} \) and \( t_s^f = \perp \)). Subscriptions in the past where generated with a probability of 60%. During the first half of the game, subscriptions for each user were generated with a rate of 3 subscriptions per hour. During the rest of the event, subscriptions were generated with a rate of 1 per hour. Unpublications and unsubscriptions, which are expected to be rare operations, were generated with a rate of 0.5 and 0.2 per node per hour, respectively, both only during the second half of the game. We crawled a total of 3 hours, starting at 20:00 2016-07-10. To make simulation execution more timely, we compressed the 3 hours of the game into 10 minutes of simulated time.

Figure 3 depicts an example of the distribution of operations in a trace file over time (100 nodes: 4545 pubs., 526 subs., 29 unpubs., 15 unsubs.). The rate at which operations are issued is not regular, having occasional spikes and moments with no operations.

Figure 3: Distribution of operations over time in a trace.
Thus, in our simulations, the application running on the nodes only starts after 30 seconds. Then, nodes begin to join the system, randomly, in the next 30 seconds. Operations start being issued only after this. At the end of the simulation, nodes only shutdown 60 seconds after operations have stopped being issued. Thus, the total simulation time is 720 seconds. Both versions of Thyme execute the same traces and use the same methodology.

6.3 Stable and Static Nodes

In Figure 4, we can observe the impact that both materializations of Thyme have on the lower layers of the network stack. Figure 4a reports the total traffic transmitted by all the nodes (at the physical layer—PHY), during the simulation. The PL/SG version presents quite an overhead. With 196 nodes, it reports more than the double of the transmitted traffic by the DCS version. Since we are targeting mobile devices, energy is a valuable resource. Looking at this in an energy perspective, PL/SG will spend twice the energy to do roughly the same work.

Figures 4c and 4d depict values reported by the link layer—MAC. The Wi-Fi MAC layer implements CSMA/CA and a per hop retransmission mechanism. In Figure 4d, we can see the total number of retransmitted packets. Figure 4c shows the total number of packets that exceeded the maximum number of retransmission attempts. These figures show us, to some extent, the amount of interference generated by the system itself. The flooding strategy of PL/SG causes a great amount of retransmissions. Lost messages in a wireless communication medium are inevitable. DCS also causes many retransmissions, but far less than PL/SG.

Figure 4b depicts the total traffic forwarded by every node in the system. In some sense, this shows the amount of work nodes have to do on behalf of the system. In this case, DCS forwards more traffic because its publish and unpublish operations also generate traffic, while in PL/SG
these are executed locally.

Figure 4 shows the total amount of control information the routing protocols transmit. PL/SG uses DSDV, a proactive routing protocol, whereas DCS uses a geographic routing protocol (a variation of GPSR). While DSDV needs to exchange lots of information to compute the shortest paths to every other node in the network, the geographic routing used by DCS routes messages using only local information. Nodes only send periodic control beacons with their geographic location (3 bytes in size). However, messages may be routed through longer routes. With 196 nodes, we can see that a quarter of all the transmitted traffic of PL/SG was control traffic.

Figure 5 depicts application level metrics. In this static scenario, we expect neither version to surpass the other. Regarding operation success ratio (Figures 5a and 5b), we verify that both versions have more than 94% success for every operation. In both versions, notifications are a type of message that does not employ an application level retransmission mechanism (§5.6). Thus, they are more susceptible to interferences, and can end up being lost.

Regarding operation latency (Figures 5c and 5d), we can see the advantage of calculating shortest paths. Notification operations have lower latency in PL/SG, because the geographic routing of DCS cannot compete with the shortest paths of DSDV. On the other hand, download operations in DCS have a slightly lower latency, because DCS causes overall less interferences and it employs a location-aware strategy when retrieving data (§5.5).

6.4 Static but Failing Nodes

Regarding churn, i.e., the ingress and egress of nodes in the system, we experiment with two different scenarios. We show the impact of nodes leaving the system definitely, e.g., nodes crashing. Secondly, we show the impact of nodes with intermittent failures thus, entering and leaving the system multiple times over time. These scenarios allow to evaluate aspects regarding data availability and persistence in the presence of node failures.

6.4.1 Permanent Failures

In this scenario, nodes are either publishers or subscribers, and publishers choose a random instant (between 200 and 300 seconds of the simulation) to leave the system abruptly.
In PL/SG, publications are executed locally. This can be an advantage, since it does not require communication. But it can also be a disadvantage, since only the publisher keeps that data. If that node fails, all the data it stored will disappear with it. Figure 6 shows exactly that. As the amount of failing nodes increases, in PL/SG, the nodes with the published data leave the system thus, the matching between subscriptions and publications is not detected. However, since DCS employs replication mechanisms, even when the publisher nodes leave the system, the matching still occurs.

### 6.4.2 Transient Failures

In this scenario, nodes are selected at random. The selected nodes alternate between periods in the on and off states. Nodes are on for periods of 120 seconds, and are off for periods of 60 seconds. When changing state, nodes have a probability of 75% of changing to the opposite state, otherwise they stay in the same state.

With nodes entering and leaving the system constantly, the operations that can be more affected are the notifications detection and the downloads. Figure 7 presents the application metrics for these two operations. Once again, since DCS employs replication mechanism, it is little affected by the intermittent churn (Figures 7a and 7c). However, PL/SG suffers from low success rate in the download operations (Figures 7b). Although the notifications are detected, when a node tries to download the data, as the amount of failing nodes increases, the probability of the data owner being off also increases. This is also accompanied by an increase in the latency of notifications (Figure 7d). In PL/SG, the matching between a node’s publications and subscrip-
tions that were issued when the node was off have to wait for the node to switch state and join the system (§4). When joining the system, in PL/SG, a node receives the subscriptions issued by all the other nodes previous to it entering the system. Then, the joining node finds the new subscriptions it received and checks if it has matching publications.

Figure 8a corroborates this, even further. The maximum latency for DCS notifications stays stable as the amount of failing nodes increases. But, in PL/SG, the maximum latency for a notification increases to values around 100 seconds with 40% of failing nodes.

Figure 8b shows a byproduct of the downloads low success ratio. With no churn, DCS forwards more traffic because its publish and unpublish operations require communication. However, with this kind of intermittent churn, PL/SG forwards much more traffic than DCS. This is due to the fact that download operations are retried (and fail) many times. This entering and leaving of nodes from the network causes routing tables to become out of date, and thus need to change more frequently.

### 6.5 Stable but Mobile Nodes

When moving, nodes use the random waypoint (RWP) mobility model, which interleaves pauses with movement. We argue that the plain RWP mobility model does not quite mimic the movement pattern people have in the kind of events we target. For instance, in a football game or a music concert, people do not move constantly. In fact, they do not move much during the majority of the event, except during intermissions. Thus, to make it more better resemble our target scenarios, we made an adaptation: every time a node is about to move, it tosses a coin do decide whether to move or not. If not moving, the node continues once again in the pause moment.

For this scenario, we consider three maximum speeds: 0.6 m/s, 1.4 m/s, and 2.5 m/s (slow walking, regular walking, and running, respectively). Only 60% of nodes are mobile, and have a moving probability of 80%.

Figure 9a shows some caveats of DCS. We can see that increasing the speed lowers the notifications success ratio. We claim this happens because every node inside a cell is supposed to have the same state and work collaboratively as one. But, the intra-cell communication primitive
is the one-hop broadcast, that is unreliable by nature. Thus, nodes inside a cell may not receive the same messages. This makes that, nodes inside the same cell can have different cell states, and thus reply different answers to the same “question”. Mobility creates even more entropy in this cell state.

Figure 9b presents a byproduct of the location-aware download strategy used by DCS. While, PL/SG is required to download data from their owners, DCS might have different replicas for download at its disposal, and it can choose the one closer to the requester.

6.6 Discussion

Due to its flooding approach, PL/SG causes far more interferences than DCS. This is exacerbated the larger is the network size. Churn is also a problem for PL/SG, because publications are executed locally. In summary, PL/SG is more suitable for smaller scenarios with no data availability requirements.

In turn, DCS takes advantage of its geographic routing to employ replication and a location-aware data retrieval strategy. However, since one-hop broadcast is unreliable by nature, the assumption that every node inside a cell have the same state, needs to be relaxed. Thus, DCS is more suitable for larger scenarios with low mobility.

7 Related Work

Much work has already been done in P/S systems, both for wired and wireless settings. However, the notions of time or persistence have not been addressed in most. In wired environments, some P/S systems explore the notion of a persistent data repository to support the delivery of notifications to disconnected clients. For this, they use proxy servers that maintain permanent connections to the broker network, and buffer any notifications received while clients are disconnected [29]. The main drawback is that clients need to reconnect to the same proxies to receive the buffered notifications.

In [3], the authors propose a P/S system that allows the retrieval of data from the past. Clients must indicate how many data items from the past they want to get. This data is replicated across several buffer nodes and may have to be collected from many of these.

In wireless settings, Chapar [11] is a P/S system for mobile ad-hoc networks. It uses a broker network (based on an OLSR overlay) to handle publications and subscriptions. It also allows notifications to be buffered in replicated data containers until their expiration time elapses or they are delivered to all their intended subscribers.

GeoRendezvous [2] is a P/S system for wireless networks that also makes use of a cluster-based GHT. However, it does not provide time-awareness nor publication persistence. It uses multiple hash functions to hash topics to different cells and allow subscribers to choose the closest cells to themselves. This is very similar to the way THYMEd uses the GHT to download objects from the closest replicas. Contrary to THYMEd, it only allows one tag per subscription.

Regarding other data dissemination mechanisms for wireless networks, Krowd [7] provides a key/value store for sharing data among nearby wireless devices. It deploys a one-hop DHT, where each device is connected to every other device, requiring complete knowledge of the network. It does not provide data replication, and is not resistant to device mobility or churn. It also does not address data availability in face of device failure.

Ephesus [27] is a decentralized key/value store for networks of mobile devices. It builds on a non-mobility-aware DHT to tolerate churn, uses data replication to address data persistence and availability, and does not require knowledge on the entire network.

iTrust [13] is a distributed system to publish and retrieve content from mobile ad-hoc networks. To publish content, a device sends the item’s whereabouts to a random set of remote peers. To obtain a content, it contacts a random set of neighbors until it finds one that knows the content’s location. Data availability is not addressed.
PDS [28] is the work that more closely relates to ours. However, it adopts a query/response interaction model, rather than P/S. PDS is designed for content-centric data discovery and retrieval on opportunistically gathered edge devices. It targets small scale networks with low to moderate mobility. Data can be widely cached at any willing and capable device, which can lead to serious storage overheads. Another important difference is that PDS does not have the notion of “publishing content”. Data is only distributed/cached if some device requests it. As a result only popular items have some availability guarantees, while less popular data may even disappear. Moreover, users must proactively search for content they want. In Thyme, users “install” their subscriptions, and as long as these are active, users will keep receiving notifications of the content published by others.

8 Conclusions

In this paper, we present the concept of a time-aware publish/subscribe (T-P/S) system where subscriptions have an associated time scope that can reside either in the future, present or past. Thus, requiring both subscriptions and publications to be persistent in the system. In the end, this conceptually merges a publish/subscribe (P/S) system with a storage system. We also present the design of Thyme, a novel extended topic-based T-P/S system for wireless networks of mobile devices. We present two different materializations of Thyme: a simplistic approach using a publish locally/subscribe globally (PL/SG) rationale; and a more intricate one, following a data-centric storage (DCS) approach using a geographic hash table (GHT) as a storage substrate. This work can be seen as a first step towards a data dissemination/sharing system for a wide-area setting like a campus, or a football stadium.

As future work, we highlight a proof of concept implementation of Thyme for networks of Android mobile devices [3], and the integration of this approach with infrastructure support whenever possible [26]. As future directions we highlight privacy and security concerns in this type of networks (mainly access control), and tackling the problem of handling large data items.

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