

# IoT Data Prefetching in Indoor Navigation SOAs

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*Internet-based Indoor Navigation Service-Oriented Architectures (IIN-SOA)* organize signals collected by IoT-based devices to enable a wide range of novel applications indoors, where people spend 80-90% of their time. In this paper, we study the problem of *prefetching (or hoarding) the most important IoT data from an IIN-SOA to a mobile device, without knowing its user's destination during navigation*. Our proposed *Grap (Graph Prefetching)* framework structurally analyzes building topologies to identify important areas that become virtual targets to an online heuristic search algorithm we developed. We tested *Grap* with datasets from a real IIN-SOA and found it to be impressively accurate.

Additional Key Words and Phrases: Internet-of-Things, Indoor Navigation, Mobile Prefetching

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## 1 INTRODUCTION

Internet of Things (IoT) refers to a large number of physical devices being connected to the Internet that are able to see, hear, think, perform tasks as well as communicate with each other using open protocols [2, 3, 16, 32]. IoT enables the development of smart applications in important domains, such as transportation, healthcare, industrial automation, emergency response and business, having significant impact on the quality of people's life and the growth of the world's economy and security [2]. Studies showed that a typical family in the developed world owns about 5-10 internet-connected devices, such as smartphones, smartTVs, smart-home devices, etc., and according to Gartner<sup>1</sup> it is expected that this number will increase to more than 500 smart devices by 2022. In order to realize this potential growth, emerging technologies, innovations and service applications need to grow proportionally to match market demands and user needs [11].

The omni-present availability of sensor-rich smartphones along with the fact that people spend 80-90% of their time in indoor environments has recently boosted an interest around the so called *Internet-based Indoor Navigation Service-Oriented Architectures (IIN-SOA)* [34]. These comprise of indoor models, such as floor-maps and points-of-interest, along with IoT-based raw data, such as wireless, light and magnetic signals, used to localize users. There are numerous IIN-SOAs ([34] provides a taxonomy), including *Skyhook*, *Google Indoor Maps*, *Infsoft*, *Indoo.rs*, *IndoorAtlas* and

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<sup>1</sup>Sept. 08, 2014, Gartner Inc., URL: <https://goo.gl/c6VTWG>

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our in-house *Anyplace* IIN-SOA<sup>2</sup>. There is a wide range of domain-specific IIN-SOAs, in domains such as in-building guidance and navigation, inventory management, marketing and elderly support through Ambient and Assisted Living [30]. Collectively, these are expected to improve location-awareness providing thus smart answers to a variety of smart transportation, smart houses and smart cities scenarios and having a remarkable role on the evolution of intelligent decision making that can improve they quality of our lives. For example, consider a smart IIN-SOA for elderly support that provides instant emergency notifications to caregivers when elderly people leave their bed at night without returning (thus being in help) or a smart IIN-SOA for an airport that can predict future traffic patterns in the terminals and allocate resources accordingly.

A major problem with collected IoT data in IIN-SOA is that this data changes very *dynamically*, requiring users to continuously synchronize their state with the IIN-SOA, in order to enjoy an accurate localization service. For instance, consider a hypothetical scenario related to the US *Library of Congress*, where a *user*  $u$  aims to interactively carry out content-based search, exploration and navigation (i.e., the user is interactively exploring the space in a “*target-less*” manner). The oblivious solution is to provide a traditional IIN-SOA ( $s$ ) that can perform the queries in the cloud. Unfortunately, Internet connectivity in indoor spaces is *intermittent* due to inadequate Wi-Fi coverage, blockage of 3G/LTE signals, etc. As such,  $u$  cannot reach  $s$  on an ongoing basis to refine upcoming search and navigation targets as these emerge. An alternative to cloud-based search, is to hoard the complete IoT data on the mobile app of user (i.e., by caching it a priori). Unfortunately, IoT data is *massive* and *dynamic*, making complete hoarding a resource-wasteful, time-consuming and error-prone solution, due to outdated data. *Clearly, there is a need to strike a balance between these two alternative solutions, the solution of no hoarding and the solution of full hoarding.*

In this paper, we study the problem of *prefetching (or hoarding) the most important IoT data blocks from an IIN-SOA  $s$  to a mobile user  $u$ , without knowing the target of  $u$  during navigation*. Such a prefetching functionality is of paramount importance for the maintenance of a reliable IIN-SOA, because mobile devices suffer from intermittent Internet connectivity. This results in high latencies for accessing the IIN-SOA and subsequently to location inaccuracies. Our proposed framework, named *Grap (Graph Prefetching)*, decides which pieces of the IoT data space are required by a user during navigation in two steps: (i) an offline pre-processing step, named *createDG*, during which a target building is structurally analyzed as a graph to identify important areas in a target building; (ii) an online search step, named *Graph-Distance A\*-based (GDA)* algorithm, during which these multiple “virtual” targets are iteratively explored using domain-specific indoor heuristics. *Grap* results in an intelligent prefetching service that hoards spatial indoor context on the mobile device of  $u$  whenever  $u$  has network connectivity. In cases of intermittent connectivity,  $u$  localizes itself from its local hoarded data.

A preliminary formulation of the *IoT data prefetching* problem has appeared in our previous work [13]. Our prior work was established on the assumption that historic user trajectories inside buildings were available to solve this problem efficiently. In practice however, such user trajectories are hard to obtain due to rising privacy concerns [12] and respective legislation (e.g., EU General Data Protection Regulation). Additionally, even though the discussion and examples in our paper only focus on indoor spaces, situated within a building and isolated from the outside world through some physical door, our propositions can be extended into outdoor spaces as well, which also aim to support effective offline support for the disconnected workforce. For example, even though Google Maps maintains centrally public transportation timetables, predicted traffic, satellite or terrain tiles, labels and description of POIs, none of these are available, at the time of this work, when a user is operating in offline mode. The *IoT data prefetching* propositions of this work could therefore provide

<sup>2</sup>Anyplace, URL: <https://anyplace.cs.ucy.ac.cy/>

a way for a user to download the most relevant data blocks from the navigation service, providing full resolution to the available data and taking into account issues of intermittent connectivity and limited data availability. Overall, our contributions in this work are summarized as follows:

- We propose a generalized framework, named *Grap*, for prefetching IoT-based location data that yields high prefetching accuracy and high localization performance under intermittent network connectivity.
- We propose a Dependency Graph generation technique, named *createDG*, during which a target building is structurally analyzed in an offline manner to determine the most significant parts of a building. We also propose *GDA*, which is a multi-target Graph-Distance A\*-based algorithm that chases multiple targets iteratively using indoor domain-specific heuristics.
- We evaluate our design with extensive experimentation and analysis on real datasets that we obtained through an open source indoor navigation architecture (IIN-SOA) that we have developed over the years and that has won several awards for its accuracy and utility [33].
- We show how *Grap* has been integrated to an open source IIN-SOA. This exercise has helped us to validate that our propositions are practical and can be implemented in a real system.

The remainder of the paper is organized as follows: Section 2 provides background details and related work on IoT-based IIN-SOA, prefetching and graph-based algorithms. Section 3 provides our system model and formulates the problem. Section 4 presents the *Grap* framework and describes the proposed techniques that compose it. Section 5 provides an overview of our real prototype system. Section 6, presents our experimental methodology and results while Section 7 concludes the paper.

## 2 BACKGROUND AND RELATED WORK

In this section, we provide background and related work on IoT-based IIN-SOA, prefetching and graph-based algorithms, upon which our presented techniques are founded.

### 2.1 IoT-based IIN-SOA and Anyplace

A major characteristic of IoT is the inter-connectivity of things in the network and that the IoT architecture must ensure their proper operation in both the physical and the virtual world [16]. While this can be achieved by taking into consideration the scalability, extensibility, adaptiveness, modularity and interoperability of heterogeneous devices, things may move geographically, may need to communicate in real-time and interact dynamically [28]. Therefore, a *Service-oriented Architecture (SOA)* [16, 31], which treats a complex system as a set of well-defined simple objects of subsystems that can be re-used and maintained individually [31], is a good choice for IoT-demanding features.

An example of an IoT-based IIN-SOA is our own Anyplace [33], which follows a SOA design that allows to plug-n-play additional modules, either for extending system capabilities - by implementing new features - or for enhancing user-experience, by improving existing functionalities (e.g., map-matching and sophisticated data fusion to increase localization accuracy). The public Anyplace service has to this date supported more than 100,000 real user interactions, with many more users using its standalone installations. The Anyplace native Android application is composed of the *Navigator* and the *Logger* that can benefit from Wi-Fi fingerprinting [20, 23, 34] available under this platform. The *Logger* application enables users to record Wi-Fi readings from nearby Wi-Fi *Access Points (APs)* and upload them to our *Server* through a Web 2.0 API (in JSON). It is used by volunteers for contributing Wi-Fi data and for crowdsourcing the Radiomaps of buildings [7] (i.e., four directional fingerprinting in multiple rounds to remove noise). The *Navigator* allows users to see their current location on top of the floorplan map and navigate between POIs inside the building with high accuracy (i.e., 1.96 meters at the Microsoft Indoor Localization Competition at ACM/IEEE IPSN'14 [20]). The localization function *loc()* of Anyplace comprises of the following phases: in

the first offline phase, it records the so-called *Wi-Fi fingerprints*, which comprise of *Received Signal Strength (RSS)* indicators of Wi-Fi APs at certain locations  $(x,y)$  pin-pointed on a building floor map (e.g., every few meters). In the second offline phase, the Wi-Fi fingerprints are joint into a  $N \times M$  matrix, named the *Wi-Fi RadioMap*, where  $N$  is the number of unique  $(x,y)$  fingerprints and  $M$  the total number of APs. Finally, a user can compare its currently observed RSS fingerprint against the RadioMap in order to find the best match, either on the server side or in-situ at the smartphone device after downloading the whole RadioMap, by using known algorithms such as KNN or WKNN [15].

One fundamental drawback of the Anyplace's final RSS fingerprint comparison step is that users on-the-move require to communicate with the Anyplace service continuously over a Wi-Fi network, which negatively affects their localization *accuracy*, when there is *intermittent connectivity* [29]. The alternative of downloading at the smartphone device the massive RadioMap (e.g., WiGLE.net had 5.4 billion unique records by November, 2017) prior the localization, may potentially lead to *high overhead time*, *waste of limited smartphone battery*, as well as *high cost* due to expensive mobile data plans. Thus, this study aims at advancing the literature with intelligent prefetching techniques that allow users to carry out accurate indoor navigation in a target-less manner using only a selective portion of the IoT-based data residing on the IIN-SOA provider, which provides high performance (time and network capacity) but also resilience to intermittent connectivity scenarios.

## 2.2 Prefetching and Mobile Connectivity

*Caching* is the process of storing data locally, so that future requests for that data can be served faster. It finds applications in the complete spectrum of the computing memory hierarchy (i.e., from low-level hardware to high-level software). *Prefetching (or Hoarding)* on the other hand, is the process of *downloading* and then *storing* data locally in a cache, so that future requests for that data can be served in the event of a network failure. Prefetching was originally used in File Systems [25] for optimizing the I/O operations on a disk by caching disk blocks that will be needed in the near future. File System prefetching was also adopted by network and distributed environments such as CODA [24], which is a distributed file system that provides novel features such as the disconnected operation that makes server data available in mobile computing environments when the network connection is lost. Prefetching is also used in the Web for allowing browsers to pre-load frequently visited web links and content (like music and videos) in order to re-load them faster and therefore optimize the web navigation performance [5, 21].

In mobile networks, the connectivity in indoor spaces is often intermittent, referring to the frequent disconnection of a mobile node in random time intervals. This often occurs due to the following two reasons [29]: (i) there is a gap between the coverage of two APs and thus the connectivity experienced by mobile users passing by will likely be intermittent; and (ii) because of physical obstacles as well as high mobility patterns of the mobile users. In either case, intermittent connectivity may break data connections, if the connectivity disruption between a mobile node and an AP is long enough and the available transfer rate provided is below a certain threshold.

Several techniques have been proposed to tackle the intermittent connectivity problem in mobile networks such as mobility management [17], cooperative downloading schemes [27], AP deployment algorithms [36], prefetching [10], routing [35] or combinations of those techniques [29]. Prefetching systems in mobile networks aim at hiding the frequent disconnections and/or the latency of data transfers over poor and intermittently connected environments. In particular, a prefetching system predicts what data an application will request in the future and speculatively retrieves and caches that data in anticipation of those future needs [10]. All these prior solutions are not directly applicable to our formulated problem as we both do not have access to historic user data (used for learning and future predictions) but only data capturing the structural semantics of buildings.

## 2.3 Graph-based Search

Our proposed *Grap* (*Graph Prefetching*) framework uses preprocessed building topology graphs to search for important areas that have to be prefetched. Graph-search algorithms can be classified into: *Uninformed (Blind) algorithms* and *Informed search algorithms* [19]. Uninformed algorithms have no domain knowledge of the problem state and traverse the graph by using unsophisticated approaches that may have only information about the state, the successor function, the goal test and the path cost. Uninformed search algorithms are characterized by the order in which the nodes are visited to reach the goal-solution and include approaches such as *Random-Walk*, *Breadth-First Search (BFS)*, *Depth-First Search (DFS)* and *Iterative Deepening (ID)*. Informed search algorithms on the other hand are characterized by a *utility* in scanning the solution space to reach the goal. These algorithms utilize some kind of an evaluation function that either greedily (e.g., BFS), stochastically assess a set of options (e.g., *simulated annealing* and *hill climbing*), or an evaluation function that assesses the distance of the current solution from a target (e.g., *A\* heuristic*).

However, AI research focuses on simple *prediction* graph-related problems by applying Machine Learning (ML) techniques. For example, predicting a sub-structure of a given graph for mobility prediction of wireless users using *Artificial Neural Networks (ANNs)* or variants is proposed in [9]. The hard part in ML techniques is *training*, for example a neural network, with real annotated location trajectories because such trajectories have to be collected at scale and there are rising privacy concerns behind massive location tracking of the mobile workforce [12]. In the context of this work, we designed a framework that proposes an informed-search algorithm that is independent of sensitive user-centric data and can operate solely based on structural semantics available in building plots (i.e., no user data).

## 3 SYSTEM MODEL & PROBLEM FORMULATION

This section formalizes our system model, assumptions and problem. The main symbols and notation used in the rest of the paper are summarized in Table 1.

### 3.1 System Model

We assume a planar indoor area  $I$  containing a finite set of locations that are partially covered by a set of Wi-Fi APs  $\{ap_1, ap_2, \dots, ap_M\}$ . Each  $ap_i$  has a unique ID (i.e., MAC address) that is publicly broadcast and passively received by anyone moving in the coverage of  $ap_i$ . The signal intensity at which the ID of  $ap_i$  is received at location  $l$  is termed the *Received Signal Strength (RSS)* of  $ap_i$  at  $l$ , where  $-110$  indicates when an  $ap_i$  is out of reach. The set of RSS values measured and the  $ap$ -IDs read at a location  $l$  is termed *fingerprint*  $V_r$  at time step  $r$  of location  $l$ .

We further assume an indoor positioning server  $s$  that has constructed beforehand a *RadioMap* ( $RM$ ), which is a database of offline *fingerprint*  $V_l$  measured at various locations  $l \in I$ . Any subset of  $RM$  rows will be denoted as *partial RadioMap* ( $RM_r^u$ ), requested by some user  $u$  at time step  $r$ . Server  $s$  uses a localization function  $loc()$  to compute from  $RM$  (or  $RM_r^u$ ) an estimation  $\lambda_l^u$  of some new unknown location  $l'$  given the fingerprint  $V_r$ . An  $RM_r^u$  including a set of entries that are geographically close and surround  $l$  allow for a better estimation  $\lambda_l^u$  (or  $\lambda_{r'}^u$ ). Therefore, the fingerprints are spatially grouped into equal-sized blocks at  $s$  for facilitating the localization process.

Since we assumed that the arrangement of Wi-Fi APs in  $I$  results in partial coverage and weak RSS at some locations, we can define an RSS threshold  $\theta$ , below which the data transmission rate is practically zero. Such a definition will help us to articulate our analytical and experimental arguments pertinent to intermittent network connectivity. Specifically, client  $u$  with a fingerprint  $V_r$  at time step of request  $r$  is practically offline if the maximum signal strength  $max_{V_r}$  it receives from any covering

Table 1. Key Notation and Symbols

Notation	Description
$I, l$	Indoor space, Location inside $I$
$ap_i, AP, M$	Access Point $i$ , Set of all $ap_i$ , $ AP $
$s, u, U$	Localization service, User requesting localization, Set of all $u$
$r, R$	Time step of current localization request, Set of all prior $r$
$V_l, V_r$	Fingerprint (RSSs and $ap$ -IDs) at location $l$ (used in offline mapping), Fingerprint at request $r$
$RM, RM_r^u$	RadioMap mapping $V_r$ to $l$ , Partial RadioMap of $u$ at $r$ ( $ RM_r^u  \ll  RM $ )
$l_r^u, \lambda_r^u, loc()$	Actual, Estimated location of $u$ computed by $loc()$ at $r$
$\theta$	RSS threshold below which $u$ is considered disconnected from $s$
$A_r, T_r, C_r$	Point Accuracy, CPU Time and Network Capacity costs for request $r$
$\alpha, K$	Best Possible $A_r$ at $r$ , Dwell Time (time required to download $K$ data blocks)

$ap_i$  is below threshold  $\theta$ , i.e.,  $\max_{V_r} < \theta$ . Formally, this is captured by the  $connected_r$  definition that follows:

$$connected_r = \begin{cases} 0, & \text{if } \max_{V_r} \leq \theta \\ 1, & \text{if } \max_{V_r} > \theta \end{cases} \quad (1)$$

The number of blocks that can be downloaded while being  $connected_r$  depends on the amount of time that the user stays connected at  $r$ , denoted as the *dwell time*. For experimentation purposes, *dwell time* is configured to  $K$  blocks.

### 3.2 Research Goal and Metrics

**Research Goal.** Enable a mobile user to consecutively localize itself accurately and efficiently in an indoor environment, where connectivity is intermittent, using an IIN-SOA holding RM.

The efficiency of the proposed techniques to achieve the above research goal is measured by the following client-side metrics: (i) the *Point Accuracy* achieved by  $u$  while localizing; (ii) the *CPU Time* required for the localization; and (iii) the *Network Capacity* for the complete localization operation.

**Definition 3.1. Point Accuracy ( $A_r$ )** is the Euclidean error distance between the location estimation  $\lambda_r^u$  (i.e., the estimated location over the partial  $RM_r^u$ ) and the actual location  $l_r^u$  of user  $u$  (i.e., the estimated location over the whole RM) at the time step of localization request  $r$ , given by:  $A_r = |\lambda_r^u - l_r^u| + \alpha$  ( $\alpha$  is the lower bound localization accuracy achieved by any function  $loc()$ ).

**Definition 3.2. CPU Time ( $T_r$ )** is the processing time used on  $u$  for running the localization function  $loc()$  given a localization request  $r$ . This includes the time costs for transmitting/receiving the RM (or  $RM_r^u$ ) and for executing the  $loc()$  function on the mobile device.

**Definition 3.3. Network Capacity ( $C_r$ )** is the total number of messages  $|RM_i|$  needed on  $u$  for localization request  $r$ .

Our research goal can be expressed by the minimization of the following three objective functions:

$$\min F_A = \frac{1}{|R|} \sum_R A_r; \quad \min F_T = \frac{1}{|R|} \sum_R T_r; \quad \min F_C = \frac{1}{|R|} \sum_R C_r \quad (2)$$

### 3.3 Baseline Approaches

Existing techniques for indoor localization using Wi-Fi fingerprinting can be categorized as follows:

**(i) Server-side approach (SSA):** In this approach,  $u$  starts out by obtaining a  $V_r$  that is shipped to  $s$ . The location estimation  $\lambda_r^u$  of  $u$  is computed on  $s$  executing  $loc(V_r, RM)$ , and transmitted back to  $u$ . In this approach, the values of the objective functions  $F_T$  and  $F_C$  are *minimum*, as we will show in both the performance analysis and evaluation sections, given that  $u$  does not carry out any computation. The drawback of this approach is that it suffers from intermittent connectivity. Particularly, in the case of successful communication the best possible localization can be achieved by  $loc()$  using  $RM$  (i.e., the case where Point Accuracy  $A_r = \alpha$ ). Otherwise, the location estimation of  $u$  at time step  $r'$  (i.e.,  $\lambda_{r'}^u$ ) can only be inferred upon the last estimation computed, i.e.,  $A_r = |\lambda_{r'}^u - l_r^u| + \alpha$ . We observe that the parameter  $A_r$  grows worse as  $u$  moves further away from  $l_r^u$ . Therefore, in the SSA approach the objective function  $F_A$  for Point Accuracy *grows* worse, as  $\theta$  gets smaller.

**(ii) Client-side Approach (CSA):** In this approach,  $u$  downloads the whole  $RM$  from  $s$ . Assuming that the download process has completed,  $u$  can obtain a localization estimate by obtaining a  $V_r$  that is compared against  $RM$ . This approach minimizes the objective function  $F_A$ , since it achieves the best possible Point Accuracy  $A = \alpha$  and it is not affected by intermittent connectivity. The drawback of the CSA is that the objective functions  $F_T$  and  $F_C$  are *maximum*, as we will again show in both the performance analysis and evaluation sections, given that  $u$  has to both download the complete  $RM$  but also delay its computation by going through the complete  $RM$ . Although this is a one-time cost, which might seem bearable for continuous localization, it can still be prohibitive in real-world scenarios where  $RM$  changes quickly over time or for complex building structures.

## 4 THE GRAP FRAMEWORK

In this section, we describe our general Graph Prefetching (*Grap*) framework and discuss its various parameters and techniques.

### 4.1 Outline of Operation

The *Grap* framework comprises of the following conceptual steps (see Fig. 1): (i) it structurally analyzes building topologies yielding a Dependency Graph (DG) that represents the probability/likeliness of users visiting other nodes in the building. This can be calculated using problem-specific information such as structural information of a buildings or even historical traces as we used in [13]; (ii) a proposed GDA algorithm then finds the nodes with the highest probability to be visited from the current location of  $u$ ; (iii) the fingerprints falling within the selected nodes form a partial RadioMap  $RM_r^u$ ; and (iv) in connected operation,  $u$  forwards its fingerprint  $V_r$  to server  $s$  and receives its location  $\lambda_r^u$  and  $RM_r^u$  while in disconnected operation,  $u$  calculates  $\lambda_r^u$  locally using only the prefetched  $RM_r^u$ . Using the above framework, *Grap* prefetches a small group of RadioMap entries (*partial RadioMap*) on  $u$ , which can aid localization at  $u$  in case it loses connection to  $s$ . In this way, it overcomes the drawbacks of both SSA and CSA discussed in the previous section.

### 4.2 Graph Distance A\* (GDA) Algorithm

In this subsection, we discuss our proposed *Graph-Distance A\** (*GDA*) algorithm and its major components, namely the *createDG()* technique for generating the dependency graph  $DG$  and the *graphSearch()* technique for selecting the best possible partial radiomap  $RM_r^u$ . We also discuss how each single parameter of *GDA* influences its performance in terms of the three performance metrics we defined in Section 3, i.e., Point Accuracy  $A_r$ , CPU time  $T_r$  and Network Capacity  $C_r$ .

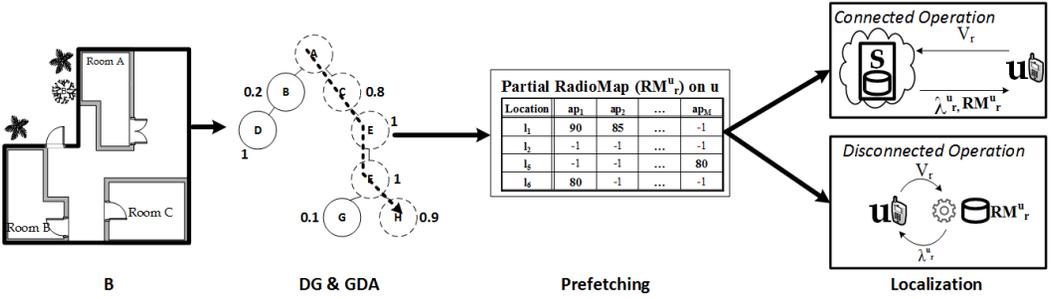


Fig. 1. The conceptual steps of the proposed Grap framework.

**4.2.1 Dependency Graph generation.** The  $createDG()$  technique summarized in Algorithm 1 constructs a  $DG$  and connects the nodes through physical transitions by consulting the actual plan  $B = \langle N, E \rangle$  of the building (we ignore the associated raster graphic of the building). The  $N$ -set contains the *Points-Of-Interests (POIs)*, which refer to rooms, intersections, elevators, staircases, etc., in the building as these have been provided by architects or crowdsourcers (so these are always up-to-date). The  $E$ -set contains the corridors, physical pathways, etc., as these are aligned to floors inside a building. The  $DG$  has been proposed to represent the connectivity on indoor *POIs* as well as the *POIs* importance in a building (with respect to the probability to be visited) and the *POI-to-POI* distances. Formally, the  $DG$  is defined as a weighted undirected graph  $DG = \langle N', E' \rangle$ , where:

- (1)  $N'$  is the set of nodes, each corresponding to a *POI* along with a *self-importance*  $s(n_i)$  weight indicating its probability to be visited by a random user. Formally,  $N' = \forall(n_i, s(n_i))$ .
- (2)  $E'$  is the set of edges, each corresponding to an *edge* along with an *edge-weight* indicating the  $L_p$ -Norm distance between two connected nodes. Formally,  $E' = \forall((n_i, n_j), d(n_i, n_j))$ .

The  $createDG()$  technique assigns weights to all nodes (lines 3 to 12 of Algorithm 1) by estimating their self-importance in terms of how likely users pass from a particular node (a.k.a. authority hub) to reach their destination. The algorithm also uses a *damping factor* ( $df$ ) to capture a probability of a random user to continue navigating at any step of the iterative computation. In particular, the importance of a node is defined iteratively and depends on the degree (*number of links*) of that particular node as well as on how many nodes in  $N$  can be visited via that node (i.e., the so called *horizon*) in order to favor nodes with low number of links but high betweenness (such as nodes that bridge two buildings or central corridors). This differentiates our approach from similar approaches like the PageRank algorithm [6], which does not use any horizon or outlook during its computation process. Finally, the  $createDG()$  technique assigns weights to all edges by calculating the Euclidean distance between them (lines 13 to 15 of Algorithm 1).

**4.2.2 Partial Radiomap selection.** In this section, we design an  $A^*$  search approach using domain-specific indoor heuristics, to explore the  $DG$  generated in the previous subsection in order to find the best nodes that  $u$  should prefetch from  $s$ .

In an intermittently-connected environment where  $u$  might be in a disconnected state during the next time step,  $u$  greedily hoards as much data as possible from  $s$  before being disconnected. An  $A^*$  search algorithm comprises of an evaluation function  $f(a, z) = g(a, b) + h(b, z)$ , where  $g(a, b)$  denotes a cost function that gives the path cost from the start node  $a$  to intermediate node  $b$  and  $h(b, z)$  a heuristic function that estimates the cheapest path from  $b$  to the goal  $z$ . In our context, both  $g()$  and  $h()$  are calculated using the graph-distance cost  $G_2$  [4, 18], which reflects the topological constraints and physical entities of a building, such as elevators, corridors, walls, etc., given that

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**Algorithm 1** *createDG()*: builds the dependency graph
 

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**Input:** Building plan  $B = \langle N, E \rangle$ : un-weighted graph,  $t$ : convergence iterations

**Output:** Dependency Graph  $DG = \langle N', E' \rangle$ 

```

1:  $nb \leftarrow neighbors(B)$  ▷  $nb$ : set of neighbors for each node
2:  $vs \leftarrow horizon(B)$  ▷  $vs$ : horizon set for each node
3: for all  $n_i \in N$  do ▷ Step 1: Calculate Node Weight Set  $N' = \forall(n_i, s(n_i))$ 
4:    $s(n_i) = |nb(n_i)| + |vs(n_i)|$  ▷ initialize self-importance of node  $n_i$ 
5: end for
6:  $df \leftarrow 0.85$  ▷  $df$ : damping factor
7: while  $t > 0$  do
8:   for all  $n_i \in N$  do
9:      $s(n_i) = \frac{1-df}{|N|} + df \times \sum_{n_j \in nb(n_i)} \frac{s(n_j)}{|nb(n_j)|}$  ▷ iteratively refine self-importance of node  $n_i$ 
10:   end for
11:    $t \leftarrow t - 1$  ▷  $t$ : alternatively, iterate until  $\sum_{n_i \in N} (\|s(n_i)_t - s(n_i)_{t+1}\|_2) < t$ 
12: end while
13: for all  $(n_i, n_j) \in E$  do ▷ Step 2: Calculate Edge Weight Set  $E' = \forall((n_i, n_j), d(n_i, n_j))$ 
14:    $d(n_i, n_j) = \sqrt{(n_i - n_j)^2}$  ▷  $d$ : any  $L_p$  norm distance metric (e.g., Euclidean distance)
15: end for

```

---

the  $L_p$ -norm distances (e.g., Euclidean, Manhattan) are unsuitable. For example, assume two nodes  $n_i, n_j$ , and an edge  $(n_i, n_j)$  on the graph if and only if there is a physical transition between the two nodes. The Euclidean distance  $L_2$ -norm is equal to the line segment directly connecting them. In cases, where the path between  $n_i$  and  $n_j$  contains some intermediate nodes (i.e.,  $n_i \rightsquigarrow n_j$ ) then the distance between them, denoted as graph distance estimation  $d(n_i \rightsquigarrow^{G_2} n_j)$ , is not a direct line from  $n_i$  to  $n_j$ , but the summation of the Euclidean distances from start node  $n_i$  to  $n_j$ .

In Algorithm 2 we present the detailed steps of the GDA algorithm (i.e., also denoted as graph-Search()) executed once per time step  $r$ . It is important to recall the fact that we aim at finding the best nodes to be prefetched in a *target-less manner* before  $u$  is disconnected from  $s$  and therefore there is *no goal state* for  $h()$  to be calculated. In line 1 of Algorithm 2 we show how in the absence of a target, the *graphSearch()* technique initially finds  $m$  virtual targets that represent the  $m$  most possible destinations of  $u$  based on its current node location ( $n_u$ ). The technique selects those  $m$  destinations based on their self-importance  $s(n_i)$  of  $DG$  presented in the previous subsection. It is important to explain that these  $m$  destinations are selected within  $w$  hops from  $n_u$  so that these are not very far destinations (we use the notation  $w^{no}$  to refer to an unlimited window).

After the  $m$  virtual targets are selected and data structures are initialized, in lines 6-19 our  $A^*$  approach aims to identify the best possible targets to be explored next using two sets (an *openSet* used for nodes to be evaluated and a *closedSet* used for nodes already evaluated). In an intermittently-connected environment, where  $u$  might be in a disconnected state during the next time step,  $u$  has to greedily hoard as much data as possible from  $s$  before being disconnected. This idea is at the algorithmic level shown by line 6. In line 7-9, we iterate over the next possible intermediate nodes one node at a time. For each explored node we calculate  $g()$  from a current location  $n$  to each neighboring node  $n_i$  and calculates  $h()$  by running the Dijkstra algorithm to find the shortest path in terms of  $G_2$  from  $n_i$  to each potential target  $n_j, j = 1, \dots, m$  in lines 10-14 of Algorithm 2. The node  $n_i$  with the lowest  $f()$  is recorded in line 15. Given that the user might disconnect at any given moment of the above algorithm execution, the server  $s$  streams results back to user  $u$  as these become available (i.e.,

---

**Algorithm 2** GDA:=*graphSearch*(): executed at each  $r$  and generating a new  $RM_r^u$  while  $u$  is moving

---

**Input:**  $DG = \langle N, E \rangle$ ,  $RM$ ,  $n_u$ : user current location,  $m$ : number of virtual targets

**Output:** Partial Radiomap  $RM_r^u$

```

1:  $H_m \leftarrow \text{top}(\text{sort}(\text{find}(n_u, w, DG)), m)$      $\triangleright$  identify virtual targets in DG  $w$  hops away from  $n_u$ 
2:  $\text{resultSet} := \{\}; \text{openSet} := \{n_u\}$      $\triangleright$  set of nodes evaluated in GDA; set of nodes to be evaluated
3:  $g(n_u, n) = 0$      $\triangleright$  Graph Distance Cost (from  $n_u$  to some intermediate node  $n$ )
4:  $h(n, n_j) = \infty$      $\triangleright$  Heuristic Cost (from intermediate node  $n$  to a virtual target  $n_j \in H_m$ )
5:  $f(n_u, n_j) = \infty$      $\triangleright$  Total Cost (from  $n_u$  towards one virtual target  $n_j \in H_m$ )
6: while ( $\text{connected}_r$ ) do     $\triangleright u$  is connected to  $s$  at time step  $r$  according to Equation 1
7:    $n := \text{findMin}(\text{openSet})$      $\triangleright n$ : Next intermediate node (with minimal cost)
8:   for all  $n_i \in \text{neighbors}(n)$  do     $\triangleright n_i$ : Neighbor of next intermediate node
9:     if  $n_i \notin \text{resultSet}$  then
10:        $g(n, n_i) \leftarrow d(n \rightsquigarrow^{G_2} n_i)$      $\triangleright$  Graph distance cost of  $n$  to  $n_i$ 
11:       for  $j = 1, \dots, m$  do
12:          $h(n_i, n_j) \leftarrow \text{Dijkstra}(n_i, n_j)$      $\triangleright$  Heuristic cost from  $n_i$  to target  $n_j$ 
13:          $f(n_i, n_j) = g(n, n_i) + h(n_i, n_j)$      $\triangleright$  Total cost from  $n_i$  to  $n_j$ 
14:       end for
15:        $\text{add}(\text{openSet}, n_i, \min(f(n_i, n_j) | j = 1, \dots, m))$   $\triangleright$  Add  $n_i$  using its least cost towards  $n_j$ 
16:     end if
17:   end for
18:    $\text{remove}(\text{openSet}, n); \text{add}(\text{resultSet}, n)$      $\triangleright$  Evaluation for node  $n$  has been completed
19:    $RM_r^u \leftarrow pRM(\text{resultSet}, RM)$      $\triangleright$  Build  $RM_r^u$  incrementally and stream results to  $u$ 
20: end while

```

---

line 19). User  $u$  utilizes these updates to build  $RM_r^u$ , which will be used for localization in subsequent disconnected states.

One optimization is that in cases where  $w^{no}$  is used, the  $m$  destinations are not required to be updated among successive GDA executions (i.e., line 1). In order to further optimize the performance of *Grap*, a cache on the smartphone's internal storage (e.g., sdcard, flash memory) is used to keep previous  $RM_r^u$ . When this optimization process is utilized, the user checks if any of the locally cached  $RM_r^u$  can serve its localization request. This reduces the occasions where localization requests to  $s$  are initiated and thus, network resources are conserved.

**Example:** Consider the scenario in Fig. 2 where a user  $u$  is at node  $A$  and requests a  $RM_r^u$  while in a connected operation state. *Grap* constructs a dependency graph of 10 nodes  $\{A, \dots, J\}$  as illustrated in Fig. 2 (left) by analyzing some building plan. The edges represent the physical transitions between the nodes. The *createDG()* function of *Grap* selects the  $m = 3$  targets with the highest probability of being the destination to  $u$  within a window  $w = 3$ . This denotes that the targets should be at least 3 hops away from node  $A$  (i.e., the current location of  $u$ ). Let us assume that the  $m$  most promising targets (i.e., the virtual targets) are nodes  $H, I, J$  denoted with dotted circles.

In the second stage of the *Grap* framework shown in Fig. 2 (right), we invoke GDA *graphSearch()* to identify the best possible nodes to prefetch along the way to the  $m$  destinations. Let us assume w.l.o.g. that in our example scenario  $u$  is enough time to download  $K = 5$  nodes before being disconnected from  $s$ . At the beginning GDA expands all neighboring nodes of  $A$  and finds the best with respect to  $f(n)$  towards each of the  $m$  target. From the available options, node  $D$  is the best choice towards target  $H$  with  $f(D) = 21$  and node  $F$  towards targets  $I, J$  with  $f(F) = 23$  and  $f(F) = 7$ , respectively. Both  $D$  and  $F$  are selected to be prefetched in round 1. In the second round, GDA selects

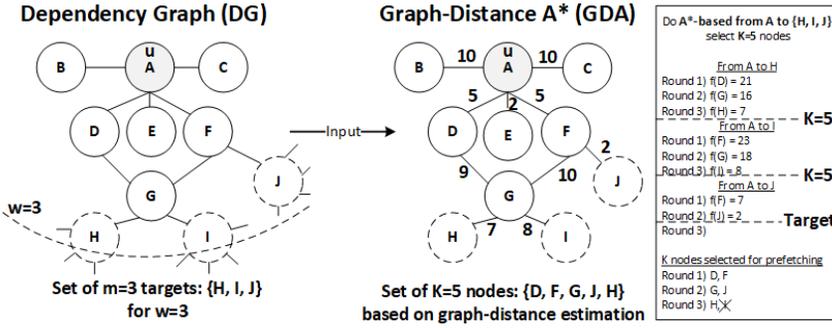


Fig. 2. Example execution of the GDA algorithm.

node  $G$  as the best choice towards targets  $H, I$  with  $f(G) = 16$  and  $f(G) = 8$ , respectively, and reaches target  $J$ . Therefore, nodes  $G$  and  $J$  are selected to be prefetched and the search towards target  $J$  stops. Finally, the algorithm selects nodes  $H$  and  $I$  as the final nodes to be prefetched with  $f(H) = 7$  and  $f(I) = 8$ , but because we have already selected four nodes to be prefetched, there is space for just one more node. GDA selects node  $H$  (and discards node  $I$ ) because its overall cost function  $f(n)$  is better.

### 4.3 Performance Analysis

We analytically derive the performance of Grap with respect to the estimated Accuracy  $A$ , CPU time  $T$  and Network capacity in messages  $C$  at the client side  $u$ . We adopt a worst case analysis as it provides a bound for all input. Our experimental evaluation in Section 6, shows that under real datasets our approach performs more efficiently than the projected worst case. The analysis is based on our system model and ignores any other performance costs not directly associated with the localization phase during the disconnected operation, any offline calculations performed by  $s$  (e.g., running the `createDG()` technique) or any idle time at  $u$  while  $s$  performs calculations (e.g., running the `graphSearch()` technique) since we consider these costs negligible. For ease of exposition, our analysis uses the notation  $\mathcal{T}^{TX}$ ,  $\mathcal{T}^{RX}$  and  $\mathcal{T}^P$  to denote the computational cost needed by  $u$  for transmitting, receiving and processing a single RM entry  $V_l$  from  $s$ .

**Lemma 1** *Grap guarantees an estimated localization accuracy of at least  $A_r = \max_{V_i \in RM} (|\lambda_i^u - l_i^u|) + \alpha$ , for a user  $u$  at a localization request  $r$ .*

**Proof.** The maximum Euclidean distance error that can be provided by the Grap framework is equal to the maximum distance between any two locations in the whole radiomap  $RM$  plus the estimated point accuracy constant  $\alpha$ . Particularly, let us assume that user  $u$  enters a building from its one end and at  $r$  requests to prefetch a partial radiomap  $RM_r^u$  from  $s$ . Server  $s$  runs our `graphSearch()` technique and generates a  $RM_r^u$  composed of the fingerprints associated to a single node around the user's initial location  $l_r^u$ . Then  $u$  moves to a location  $l_r^u$  at the other end of the building facing disconnections along the whole path. At that location,  $u$  runs the `loc()` function using the prefetched  $RM_r^u$ , received from  $s$  at the very beginning, and calculates an estimated user location  $\lambda_r^u$  that is the farthest location available in  $RM$  with respect to  $l_r^u$ . In this worst case scenario, Grap provides a  $A_r = |\lambda_r^u - l_r^u| + \alpha$   $\square$

Similarly to Lemma 1, CSA guarantees the best possible localization accuracy  $A_r = \alpha$  because  $u$  has downloaded the complete  $RM$  and thus  $\lambda_r^u = l_r^u$  for every  $r$ . On the other hand, SSA has a similar worst case accuracy bound as the Grap framework given that it also does not have the complete  $RM$ .

**Lemma 2.** *The Grap framework has a computational cost of  $O(\mathcal{T}^{TX} + I' \cdot M \cdot \mathcal{T}^{RX} + I' \cdot \mathcal{T}^P)$ , where  $I'$  is the number of RM entries retrieved from  $s$  and  $M$  the number of RM dimensions.*

**Proof.** During the connected operation,  $u$  sends a request for localization to  $s$  spending  $\mathcal{T}^{TX}$  time. Then  $s$  responds to  $u$  with an estimated location  $\lambda_r^u = (x_u, y_u)$  of size equal  $\mathcal{T}^{RX}$ , as well as  $I' \ll I$  database entries, where each entry has  $M + 2$  values, therefore  $u$  spends  $I' \cdot M \cdot \mathcal{T}^{RX}$  time. The  $I'$  entries represent the fingerprints associated with the nodes selected by our GDA approach to be prefetched by  $u$ . Finally, during the disconnected operation  $u$  localizes itself using the  $I'$  entries spending  $I' \cdot \mathcal{T}^P$ . We can safely assume that  $I' < I$ , therefore, adding all computational time costs in an asymptotic manner yields  $O(\mathcal{T}^{TX} + I' \cdot M \cdot \mathcal{T}^{RX} + I' \cdot \mathcal{T}^P)$   $\square$

Similarly to Lemma 2, CSA has a *max* computational cost  $O(\mathcal{T}^{TX} + I \cdot M \cdot \mathcal{T}^{RX} + I \cdot \mathcal{T}^P)$  and SSA a *min* computational cost  $O(\mathcal{T}^{TX} + \mathcal{T}^{RX})$  for each  $r$ . The message cost for all three techniques CSA, SSA and Grap is thus  $O(I)$ ,  $O(1)$  and  $O(I')$ , respectively.

## 5 GRAP PROTOTYPE IMPLEMENTATION

In this section, we describe the system that we implemented to evaluate the efficiency of the *Grap* framework and to validate that our propositions can easily be integrated in a real system. Our system comprises of the Grap Evaluator and the Grap Navigator. Both components were implemented on-top of our in-house *Anyplace* IIN-SOA, which allows entities (i.e., users, companies, organizations, etc.) to realize indoor information management systems, including product search and point of interest (POI) navigation, on top of existing wireless network infrastructure by leveraging rich multi-sensory data available on smartphones (see Section 2.1).

### 5.1 Grap Evaluator

The aim of the *Grap Evaluator* is to allow trace-driven evaluation and visualization of the presented techniques with data available through the public *Anyplace* IIN-SOA. The evaluator comprises of a *Data Connector*, a *Simulator* and a *Visualizer*. The data connector connects to *Anyplace* and downloads IoT-data available through its open API. For this task we had to introduce some new JSON endpoints to *Anyplace*. The *Simulator* then implements all the algorithms along with evaluation metrics discussed in the next section. The *Visualizer* shows the graph generated by various building plans (e.g., see Fig. 3) but also allows tracing the presented algorithms to understand their behavior. All components were written in JAVA, compiled using JDK 8.0 and comprise of  $\approx 16,040$  lines-of-code (LOC). After concluding our trace-driven experimentation, we ported the prefetching algorithms to an android client app presented next.

### 5.2 Grap Navigator

The aim of the *Grap Navigator* was to create a proof-of-concept realization of our propositions in a real mobile indoor search, exploration and navigation tool. We particularly adapted the *Anyplace* navigator with options to introduce intelligent prefetching and caching. The installation package of the *Grap* android client we developed was only around 5MB. Overall, our code consists of approximately 34,575 LOC, including 2010 lines of XML elements that go in the Manifest file (settings) and the user interface XML descriptions of the navigator.

Our prototype GUI in Fig. 4 allows a user to select the prefetching functionality in order to navigate in a building without suffering by intermittent connectivity along with supplementary control features that are useful for demonstration purposes. The GUI allows a user to visualize the  $RM_r^u$  prefetched at each localization step on a map. The interface uses the actual plan of a building and overlays a heatmap that represents the signal strength values in dBm collected from nearby APs (i.e., the fingerprints) and prefetched on the user's smartphone. Fig. 4 (right), shows a heatmap of

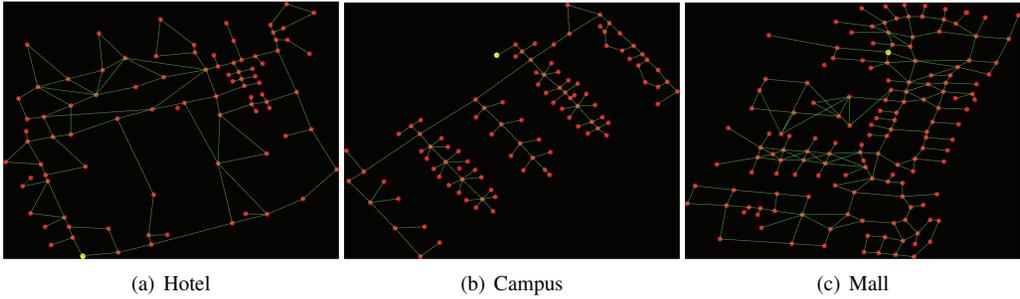


Fig. 3. *Datasets*. The topologies of the three datasets obtained through the Anyplace IIN-SOA JSON API. The visualization is carried out with the Grap Evaluator/Visualizer.

the partial-radiomap prefetched on the mobile device, which is considerably smaller in size than the fingerprints of all floors.

## 6 EXPERIMENTAL EVALUATION

This section presents an extensive experimental evaluation of our proposed Grap framework. We start-out with the experimental methodology and setup, followed by our experimental studies.

### 6.1 Methodology

**Real Datasets:** We constructed three realistic datasets from three real IoT-data obtained through the publicly available API of our Anyplace IIN-SOA described in Section 2.1.

*Hotel Pittsburgh:* This datasets was collected at the Wyndham Grand Pittsburgh Downtown Hotel in Pittsburgh, PA, USA. In particular, it consists of around 500 reference fingerprints taken from  $\sim 308$  Wi-Fi APs installed in the two floors of the hotel and neighboring buildings. The structure of the hotel is of a rectangular shape as shown in Fig. 3a, it covers around  $6,500 m^2$  and consists of 201 POIs and 247 edges.

*Campus CSUCY:* This datasets was collected at the Department of Computer Science (CS), University of Cyprus. In particular, it consists of 5,000 reference fingerprints taken from  $\sim 266$  Wi-Fi APs installed in the four floors of the CS and neighboring buildings. We collected our data by walking over a path that consists of  $\approx 2,900$  locations. The structure of the CSUCY campus is of a bus-like shape as shown in Fig. 3b, it covers around  $2,500 m^2$  and consists of 397 POIs and 440 edges.

*Mall of Cyprus:* This datasets was collected at the Mall of Cyprus. In particular, it consists of 800 reference fingerprints taken from  $\sim 279$  Wi-Fi APs installed in the two floors of the mall and neighboring buildings. The structure of the mall is of a mesh-like shape as shown in Fig. 3c, it covers around  $18,500 m^2$  and consists of 214 POIs and 289 edges.

**User Traces:** In order to evaluate the scalability of our propositions we generated realistic user traces of various scales where a user follows and localizes at pre-defined locations. The traces are designed for our evaluation study, in order to show the performance vs. accuracy trade-off in using Grap. Particularly, the distinct locations are of fixed distance between each other (e.g., around 5 meters) and the size of traces varies from 15-30 localizations steps (i.e., a user moving in a multi-floor building and travels around 50-150 m). The RadioMap is also spatially grouped into equal-size blocks that correspond to the POIs of a particular building. Both the traces and blocks can be viewed and verified using the Grap visualizer described in Section 5.

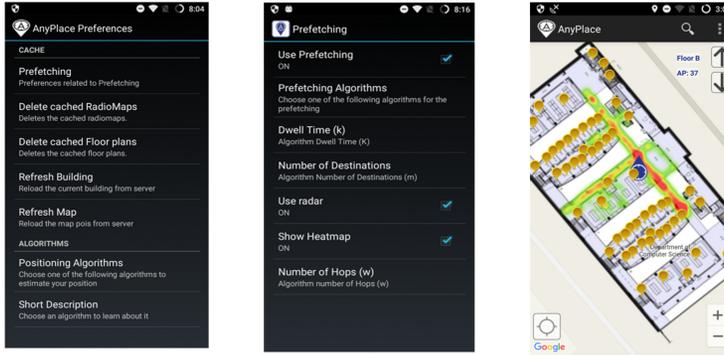


Fig. 4. The Grap Navigator (left) showing the menu for switching the prefetching feature on/off; and (center) varying the GDA parameters; (right) viewing the prefetched IoT data and user's location.

**Algorithms:** We compare the proposed Grap framework with two Anyplace (no-prefetching) baseline approaches and two Grap (with prefetching) baseline approaches.

*Anyplace (no-prefetching) baseline approaches:* *Server-Side Approach (SSA)* and *Client-Side Approach (CSA)*, as described in Section 3.3, do not prefetch any localization data since the former keeps the whole *RM* at the server-side and the latter downloads the whole *RM* on the mobile device of the user *u* prior localization.

*Grap (with prefetching) baseline approaches:* The proposed *Graph Distance A\** approach (*GDA*) of the *Grap* framework, as described in Section 4, the *Breadth First Search (BFS)* approach that selects nodes to be prefetched level-by-level based on user's current location starting from the neighbor nodes before moving to the next level nodes and the *Random (RND)* selection approach, which selects nodes to be prefetched randomly.

**Metrics:** Our cost metrics are: *CPU Time (T)*, *Location Accuracy (A)* and *Network Capacity (C)* as defined in Section 3.2. The mean and standard deviation of the results is shown with error bars in all experimental studies that follow, each entailing 37 localization steps (i.e., the route length of trajectories in our experiments).

**Parameters:** In all experiments that follow the simulation parameters were configured as follows: dwell time  $K = 15$  (i.e., time required to download  $K$  data blocks), number of virtual targets  $m = 3$ , lookahead window  $w = 3$ , effective network threshold  $\theta = -40\text{dBm}$  and localization method = *WKNN*. The influence of each of those parameters on the proposed approach is investigated individually in Experiments 2-5 (Subsections 6.3 to 6.6) by fixing the rest of the parameters accordingly.

## 6.2 Experiment 1: Performance Evaluation

In the first experiment, our main target was to assess the performance objectives *A*, *T* and *C* for the compared algorithms. As shown in Fig. 5, the no-prefetching approaches *CS* and *SS* are the extreme cases, providing the best *A* and the best resources consumption, respectively, demonstrating a clear trade-off between *A* vs. (*T* and *C*). The proposed *GDA* approach of the *Grap* framework performs well ( $< 5m$ ) and better than both prefetching *RND* and *BFS* approaches in all datasets. In particular, *GDA* provides an average  $A = 1.84m$  in the Hotel dataset that is an improvement of 65% w.r.t. *RND* and 40% w.r.t. *BFS*. In the Campus dataset, *GDA* provides an average  $A = 1.26m$  that is an improvement of 83% w.r.t. *RND* and 60% w.r.t. *BFS*. Finally in the mall dataset, *GDA* provides an average  $A = 4.52m$  that is an improvement of 68% w.r.t. *RND* and 50% w.r.t. *BFS*. The accuracy

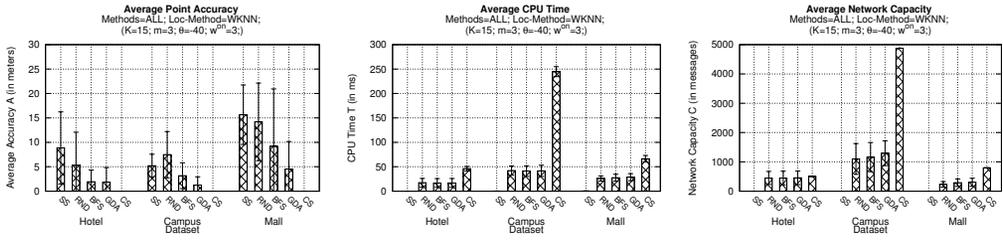


Fig. 5. **Experiment 1 - Performance Evaluation:** GDA evaluation in terms of average Point Accuracy  $A$  (left), average CPU Time  $T$  (center) and Network Capacity  $C$  (right) in all datasets.

of  $GDA$  is relatively close (i.e., 2.54m, on average) to the best possible localization  $A$  of the  $CS$  approach and provides an improvement of at least  $> 70\%$  in all three datasets over the  $SS$  approach. This shows that  $GDA$  calculates and prefetches an almost best set of fingerprints (partial radiomap  $RM_r^u$ ) and therefore it successfully overcomes the intermittent connectivity issues.

We observe that all approaches sacrifice performance (i.e.,  $T$  and  $C$ ) for the sake of better quality (i.e.,  $A$ ). The  $CS$  approach requires the highest  $T$  (118.6 msec, on average) and  $C$  (2060 messages, on average) since it downloads the whole RadioMap (the actual numbers are summarized in subsection 6.1) and uses all fingerprints at each localization step. For the Campus dataset, which entails one order of magnitude more fingerprints, this drawback is even more apparent. The prefetching approaches including the proposed  $GDA$  require less  $T$  and  $C$  than  $CS$ , since they utilize a partial RadioMap, and more resources than  $SS$  that does not download any fingerprints and does not calculate its location locally at the client side. In particular,  $GDA$  requires 28 msec more  $T$  and 683 more messages, on average, compared to  $SS$ . In some cases the proposed  $GDA$  approach consumes slightly more resources than the other two prefetching techniques due to the fact that it performs more sophisticated computations (e.g., calculates the graph distance towards  $m$  destinations, etc.) to calculate the  $RM_r^u$  than the  $RND$  and  $BFS$  approaches. However, the slight increase on the resources consumption offers much better  $A$ , as discussed earlier.

### 6.3 Experiment 2: Dwell Time ( $K$ )

Experiment 2 examines how dwell time  $K$  influences the behavior and the performance of the proposed  $Grap$  framework. Recall that  $K$  represents the available time for downloading the fingerprints associated to  $K$  nodes of the  $DG$  and therefore represents the size of the partial radiomap  $RM_r^u$  that is downloaded by  $u$  when connected and processed by  $u$  when in a disconnected state. In particular, in this experiment we evaluate the performance of all prefetching approaches ( $RND$ ,  $BFS$  and  $GDA$ ) that incorporate the  $K$  parameter in their solution in terms of  $A$ ,  $T$  and  $C$ . We also include the performance of the no-prefetching (i.e.,  $CS$  and  $SS$ ) approaches that are independent of  $K$  for comparison purposes.

Fig. 6 (left) shows that all prefetching approaches are positively affected by the increase of  $K$  since high  $K$  means that there is more time to download more fingerprints for a more fine localization. However, this negatively affects the two performance metrics (i.e.,  $T$  and  $C$  in Fig. 6 (center) and (right)) since the increase of  $K$  results in more fingerprints to be downloaded during a connected state and a larger  $RM_r^u$  to be processed while localizing in a disconnected state. Moreover, the results in Fig. 6 also show that the delicate selection of fingerprints by the proposed  $GDA$  approach overwhelms the absence of a large number of fingerprints when  $K$  is small since the provided  $A$  varies from  $6m$  for  $K = 1$  to  $0.8m$  for  $K = 20$  and therefore it is influenced less than its counterpart prefetching approaches. In particular,  $GDA$  provides an average of 75% better  $A$  than  $RND$ , around 52% than

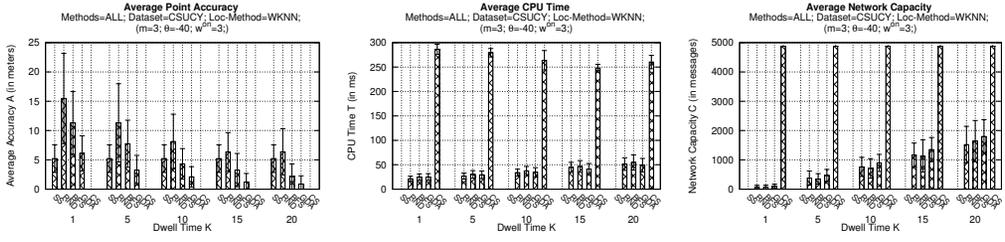


Fig. 6. **Experiment 2 - Dwell Time (K):** examining the *GDA* accuracy (left), CPU time (center) and Network Capacity  $C$  (right) while varying the Dwell Time (K).

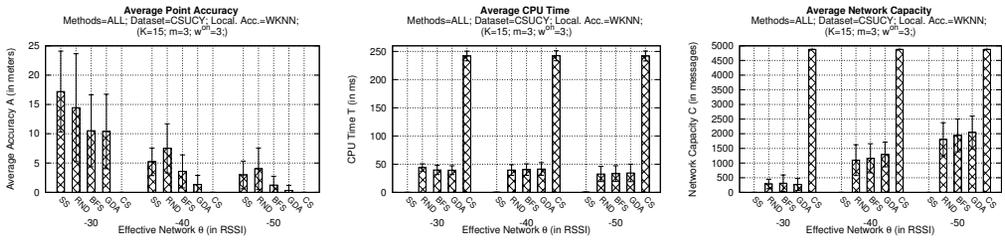


Fig. 7. **Experiment 3 - Effective Network ( $\theta$ ):** examining the *GDA* accuracy (left), CPU time (center) and Network Capacity  $C$  (right) while varying the effective network  $\theta$  threshold.

*BFS* and it is preferable than the no-prefetching *SS* approach in all cases except the extreme case for  $K = 1$ , where the amount of prefetched fingerprint does not suffice to outweigh the *SS* approach.

Note that all prefetching approaches will reach an  $A$  equal to the best possible  $A$  of the *CS* approach when the dwell time of a localization step is enough for downloading the whole radiomap  $RM$ . This increase of  $K$ , however, results in an increase on the resource consumption with the results of the *CS* approach showing the  $T$  and  $C$  needed in the worst case. The slight variations between the prefetching approaches in terms of  $T$  and  $C$  for the same  $K$  are due to the additional effort needed for calculating the  $K$  nodes, which consequently select  $K$  different nodes with varying number of fingerprints.

Clearly, there is a trade-off between the dwell time  $K \ll N$  and the benefit (i.e., the  $A$ ,  $T$  and  $C$  metrics we defined). Particularly, with larger  $K$  better  $A$  is expected on the one hand but more  $C$  and  $T$  is spent, since  $K \rightarrow N$  and  $I' \rightarrow I$ . If user  $u$  sets  $K = N$  then  $I' = I$  and  $RM_r^u = RM$  and  $u$  will receive the whole  $RM$ . In this case, Grap is the same as the client-side approach *CSA* described earlier.

#### 6.4 Experiment 3: Effective Network ( $\theta$ )

Experiment 3 examines the sensitivity of the proposed *GDA* approach and all other approaches for various  $\theta$  parameters. Recall that the  $\theta$  parameter represents the effectiveness of the network with respect to a user being connected, meaning that the lowest the  $\theta$  of a network is, the less intermittent connectivity inside a building exists and therefore the highest the probability of user  $u$  to be connected while navigating in the building.

Fig. 7 (left) shows that all prefetching approaches are positively affected by the decrease of  $\theta$  since user  $u$  is more frequently connected and therefore communicates with the server  $s$  more often for enriching its  $RM_r^u$  with more nodes and consequently more fingerprints. The proposed *GDA* approach provides, however, the best  $A$  in all cases that increases while the  $\theta$  parameter decreases due to the

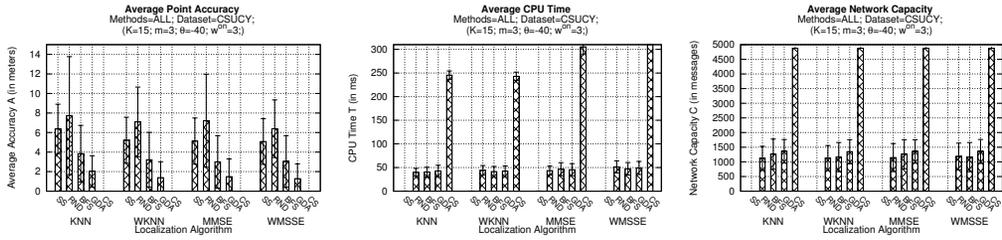


Fig. 8. **Experiment 4 - Localization Methods:** examining the *GDA* accuracy (left), CPU time (center) and Network Capacity  $C$  (right) with respect to various localization methods.

fact that it has more opportunities to download an efficient set of nodes and represent the actual path that the user will follow as well as there is an increased probability to correct possible flaws at the initial calculations. In particular, *GDA* provides a poor  $A$  of around  $10m$  for  $\theta = -30dBm$  that is 58% better than the accuracy provided by *RND* and 2% better than the *BFS* and a fine  $A$  of  $0.33m$  for  $\theta = -50dBm$  that is 75% better than the one provided by *RND* and 43% better than *BFS*. Regarding the no-prefetching approaches the *SS* is influenced from the network effectiveness more than any other approach, since for high  $\theta$ s ( $-30dBm$ ) and consequently for high intermittent connectivity,  $u$  cannot communicate with  $s$  and therefore it cannot localize and navigate in the building. Therefore, *SS* provides worse  $A$  than both *BFS* and *GDA* in all cases, due to the fact that the latter prefetch fingerprints when connected to localize at the smartphone in cases of disconnections. On the other hand, the *CS* approach is independent to the  $\theta$  parameter since  $u$  downloads the whole *RM* a priori and does not require any communication with  $s$  during navigation.

In terms of resource consumption, however, the *CS* is the worst since it utilizes maximum resources in all cases irrespectively of the actual needs of the localization process. The *SS* approach is the best in these performance metrics since it requires the minimum resources at each localization step. The most important information, however, with respect to  $T$  and  $C$  comes from the prefetching approaches since the results show that all approaches are not influenced by the  $\theta$  parameter and provide similar results in all cases. This is another major benefit of the proposed *GDA* approach since it provides considerable better  $A$  by utilizing similar resources compared to *RND* and *BFS*.

## 6.5 Experiment 4: Localization Algorithms

Experiment 4 examines the impact of various localization algorithms (i.e., *K-Nearest Neighbors* (*KNN*), *Weighted-KNN* (*WKNN*), *Minimum Mean Square Error* (*MMSE*), *Weighted-MMSE* (*WMMSE*)) available in the Anyplace IIN-SOA [34] on the performance of all approaches. Any localization technique can be used in the *loc()* step of the *Grap* framework for calculating the user's current location by utilizing a (partial) radiomap at every localization step. The results in Fig. 8 show that neither the prefetching approaches nor the no-prefetching approaches are considerably influenced by the localization algorithm since they provide similar results with respect to  $A$ ,  $T$  and  $C$  in all cases. In general, all approaches provide slightly worse  $A$  when the *KNN* algorithm is used and utilize almost negligibly more resources. In all cases, however, the proposed *GDA* approach provides better results than all prefetching approaches and successfully adopts the trade-off between  $A$  and resources consumption  $T$  and  $C$  with respect to the no-prefetching approaches *SS* and *CS*.

## 6.6 Experiment 5: GDA Sensitivity Analysis

In these experiments, we examine several control parameters of the proposed *GDA* approach and how these parameters influence its performance in terms of  $A$ ,  $T$  and  $C$ . Recall that for the Experiments 2-4

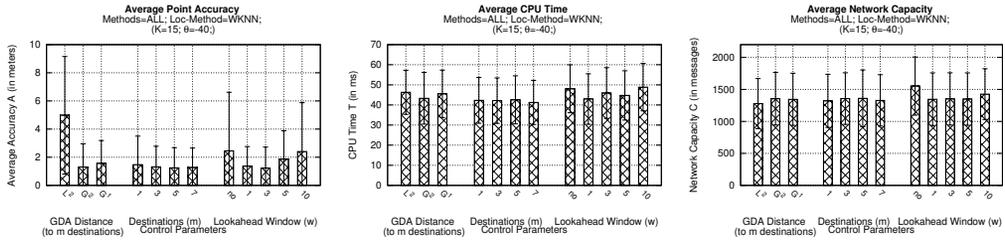


Fig. 9. **Experiment 5 - Control Parameter Experiments:** examining the *GDA* accuracy (left), CPU time (center) and Network Capacity  $C$  (right) with respect to various control parameters.

we presented above, we already evaluated the parameters that had to do with the system configuration (e.g., effective network, dwell time and localization algorithms), but not the algorithmic parameters of Grap that we carry out in this section.

The first control parameter experiment in Fig. 9 (left) studies the *GDA* distance parameter as discussed in Subsection 4.2, which is the  $h(n)$  heuristic of the evaluation function  $f(n)$  of our  $A^*$ -based approach that estimates the cost from node  $n$  to each of the  $m$  virtual targets. We examined three different  $h(n)$  heuristics: (i)  $L_2$  that calculates the Euclidean distance from  $n$  to  $m$  nodes; (ii)  $G_2$  that calculates a graph distance by using the Dijkstra algorithm; and (iii) the greedy  $G_1$  heuristic that finds the shortest path by using the (node) weights of the dependency graph  $DG$  (i.e., the self-importance). The second control parameter experiment varies the number of virtual targets  $m$  taken into consideration at each iteration. The third control parameter experiment examines the lookahead window parameter that represents the maximum distance in number of hops between the current node and the  $m$  nodes. The  $w^{no}$  means that there is no constraint in the number of hops and therefore the *GDA* approach finds the  $m$  most popular virtual targets of the whole building.

The results of the first control parameter experiment in Fig. 9 (left set of parameters at each plot - for various *GDA* distance heuristics) show that the proposed approach performs better when the graph distance  $G_2$  estimation is used, since it provides about 74% better  $A$  than  $L_2$  and 16% better accuracy than  $G_1$  utilizing less  $T$  and similar  $C$ , at the same time. This is due to the fact that the  $G_2$  heuristic can more easily adopt the constraints and explicit characteristics of an indoor environment and can more easily provide a more representative distance cost between two indoor locations. The variations on  $m$  of the second control parameter experiment in Fig. 9 (center at each plot) show that *GDA* is slightly affected by this parameter and demonstrate a slight preference for an  $m$  that is neither too high (e.g.,  $m = 7$ ) nor too low (e.g.,  $m = 1$ ). This is due to the fact that a high  $m$  means that *GDA* will have a large number of goals and therefore it may divide the limited number of  $K$  nodes that will be selected for prefetching into many paths and subsequently may result in a *BFS*-like behavior. On the other hand, with a low  $K$  there is a high probability of selecting a wrong virtual target and therefore prefetch nodes along a wrong direction. Finally, the third control parameter experiment in Fig. 9 (right at each plot - variations of the lookahead window  $w$ ) show that *GDA* prefers small lookahead window  $w$  since this means that the  $m$  virtual targets will be closer to the current location of  $u$  at each iteration and therefore it would be much more easier for *GDA* to fix a wrong decision (i.e., selecting a popular destination that is far away from the actual path that the user follows.)

## 6.7 Experiment 6: Real Prototype Evaluation

In the last experiment, we use our real prototype system on a Samsung Galaxy S3 (Android 4) using an Exynos 4 Quad (GT-I9300). Particularly, we follow 20 random routes of 15m long each in the CS UCY campus and we measure the accuracy and energy consumption. The energy consumption is

measured using PowerTutor, which according to [8] is 86% accurate. We utilize the same parameter settings as in the previous experiments, i.e., dwell time  $K = 15$ , number of virtual targets  $m = 3$ , lookahead window  $w = 3$ , effective network threshold  $\theta = -40\text{dBm}$  and localization method = *WKNN*. All messaging goes through the 802.11 Wi-Fi interface. Extensive simulation over multiple smartphones was outside the scope of this work, even though we refer interested readers to our prior work SmartLab [14], in order to assess the complex dimensions arising in testing extensively smartphone applications on multiple real smartphone devices.

In respect to average accuracy, the results are comparable to our previous results and discussions, since the accuracy varies between  $3m$  and  $10m$ . The energy consumption of our real prototype can be considered reasonable since it consumes around  $42.64J$  on average for 30 routes, which means around  $2J$  for each  $15m$  long indoor navigation or 0.06% of a fully charged battery that is much less than the 1.09% ( $\approx 35J$ ) needed to request and download the wikipedia mobile site [26].

## 7 CONCLUSIONS AND FUTURE WORK

In this paper, we study the problem of *prefetching the most important IoT data blocks from an IIN-SOA to a mobile device, without knowing its user's destination during navigation*. Our proposed framework, named *Grap (Graph Prefetching)*, structurally analyzes in an offline phase the building topology graphs to identify important areas inside building complexes (e.g., malls, hotels, campuses). The identified “hotspots” subsequently become virtual targets to an online heuristic graph search algorithm we developed, named *Graph-Distance A\*-based (GDA)*. We tested our *Grap* framework with real datasets from our production prototype IIN-SOA, which reached over 100,000 real users, and found *Grap* to be impressively accurate while retaining high performance levels (i.e., CPU time, network capacity and energy consumption). Our prototype implementation validates that our propositions are pragmatic and can easily make their way into future IIN-SOA.

In the future, we plan to investigate the trade-off between the CPU/network capacity and the accuracy objectives in the context of Multi-Objective Optimization. We also plan to extend our experimental evaluation into domain-specific field studies (e.g., involving health/hospitals, education/universities) but also deal with more realistic evaluation scenarios that would require the adaptation of the physical infrastructure behind our experiments (e.g., varying number of APs, incorporating UWB transceivers or beacons). Finally, we intent to release our developed artifacts as an open-source project.

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