VALI: An SDN-based Management Framework for Public Wireless LANs

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***Abstract*—Usage of WiFi is becoming increasingly popular in various public wireless LAN (WLAN) settings like malls, airports and train stations. Similarly to other prominent examples of WiFi usage like enterprise and home settings, public WLANs could also benefit from an SDN-based coordinated management framework that deals with issues like interference and mobility management. However, unlike these settings, public WLANs also present a few differences in their characteristics, such as the need to offer location-aware services and dynamic categorization of users, and the consequent need to provide sophisticated association strategies. Motivated by this observation we propose VALI, an SDN management framework specifically tailored to meet the needs of public WLAN settings. We begin by discussing the characteristics of public WLANs that motivate the need for a new management framework and provide an overview of VALI's architecture, highlighting its advantages compared to other existing SDN based management frameworks targeting enterprise or home settings. We present a prototype implementation of VALI and evaluate its performance through a testbed that resembles a realistic public WLAN environment. Our results demonstrate that VALI is a promising solution that could be used to effectively manage public WLAN settings and enable location-aware WiFi access.**

I. Introduction

In urban regions, usage of WiFi is widespread in public places including shopping malls, shopping streets, airports and train stations. Most of these deployments are uncoordinated since they are operated by non-cooperating retail stores or malls and are independently managed. There are many advantages to coordinated management of public WLANs. More specifically, the coordination among the access points (APs) including those that are owned/deployed by different entities can result in a wide range of benefits, such as seamless mobility, user specific (or location-aware) services, improved interference management, data offloading and so on. This can potentially improve both user experience and network performance through the efficient utilization of resources.

Currently, there exist several providers who offer WLAN deployment and management services in common/open areas of indoor public spaces like shopping centers (e.g. Inkspotwifi[1] and XCellAir [2]). Such providers do not however offer management services for already/independently deployed WiFi hotspots within specific parts (e.g., coffee shops, book stores) of the same indoor public spaces. This is due to the lack of WLAN management frameworks that can enable coordinated operation of WiFi APs owned/deployed by different entities.

Moreover, the management of public WLANs poses certain unique requirements such as prioritized and location-aware differentiated services for users. For example, a dynamic way of categorizing mobile devices can help in eliminating the login process users need to undergo while visiting each shop or different areas of a mall. Such concerns regarding the coverage and performance of public WLANs are also highlighted in two recent studies [3], [4]. We argue that by collaborative access and optimized user association in public WLANs, the network and per-user throughput as well as the overall user experience can be improved. Therefore, by designing a management framework specifically tailored for public WLANs, several key concerns raised by public WLAN users could be addressed.

WLAN management solutions in the industry mostly target enterprise deployments. For example, there are several vendor solutions available to manage enterprise WLANs in a centralized fashion (e.g., [5], [6]). However, these solutions are not designed to meet the unique requirements of public WLANs. While the SDN-based centrally coordinated and programmable management of disparate WLANs is a promising approach, existing SDN based WLAN management proposals in the literature primarily target enterprise and home WLAN settings (e.g., [7], [8]). There also exist proposals such as [9] and [10] for prioritized services in home WLANs but priority in those proposals is based on traffic and not on location as would be desirable in a public WLAN setting.

With the above in mind, we aim at developing a solution that can deal with the public WLAN requirements for location-aware differentiated services and the dynamic role changes of users in a simple yet effective manner. Towards this end, this paper makes the following contributions. Firstly, we propose VALI[1], an SDN-based management framework tailored for public WLANs. Secondly, we provide a prototype implementation of VALI as a proof-of-concept. Finally, we evaluate it in a realistic testbed setting, demonstrating its value for effectively managing public WLANs and enabling location-aware WiFi access.

II. Public WLAN characteristics

A basic characteristic of many public WLANs is the existence of multiple APs collocated in small areas, offering users the opportunity to be connected to high-speed (and in many

[1] In Norse mythology, Vali is a son of the god Odin.

cases, free) wireless Internet access while they are away from home/work. As a concrete example we consider the case of a mall, where a common practice is the deployment of APs which allow the guests of the mall, after going through some kind of registration, to have access to basic Internet services like browsing the web or checking their emails while in and moving across the mall open spaces. Since the majority of the mall guests use these APs to connect to the Internet, it is normal for them to experience poor network performance or even inability to connect.

In addition to the centrally deployed infrastructure, each shop can choose to deploy its own APs, which are intended to offer a better quality of service for their customers. For example, a coffee shop might want to allow people to stream news videos while drinking their coffee. Such an approach could also be used to offer exclusive premium services to customers, like for instance access to digital libraries of bookshops or music & video stores, so that customers can have a free preview of the content of their interest while they are still in the shop.

A major issue that rises in such a setting is the sub-optimality in the way that the wireless infrastructure is managed. The uncoordinated way in which users associate with APs and roam the area of the public WLAN, along with the unplanned manner with which the infrastructure is deployed can lead to serious performance degradation due to high interference and high network load in hotspot areas, ultimately leading to the frustration of customers. These problems are not unique to the public WLAN domain and have been extensively studied in other closely-related domains like enterprise and home settings. However, unlike these settings where the main issues come from the decentralized way of managing interference and user association, public WLANs like the one described above present a number of unique challenges. As already mentioned, in such a setting a user can assume many different roles within a short span of time, like for instance from a guest of the mall to a customer of some shop. Each of these roles comes with its own requirements in user bandwidth, as well as with a different set of rules regarding traffic. Ideally, the user should always be able to associate with the network in such a way so that these requirements can be automatically met.

A final important issue is that even though the intention of deploying an AP dedicated to premium users within a region of a public WLAN is to provide them an improved quality of service, in reality this might not always be the case as illustrated in Figure 1 for a region of a mall. Users within the gray areas expect to receive premium services offered by the corresponding shops, while users in the white areas are considered as mall guests where no guarantee of quality of service is provided. The solid lines represent the associations that users are expected to have with APs, assuming that each AP only offers one type of service, i.e., a user wishing to get the premium services and increased bandwidth offered for shop 1 customers needs to associate with the AP located in the shop. On the other hand, the dashed lines represent alternative associations for some users. Through this figure we can observe that it might be more beneficial for some guest users to be associated with an AP setup for dedicated shop usage, while similarly it might be preferable for some shop customers to associate with the guest users' AP due to better RSSI or due to a better balance in the network load.

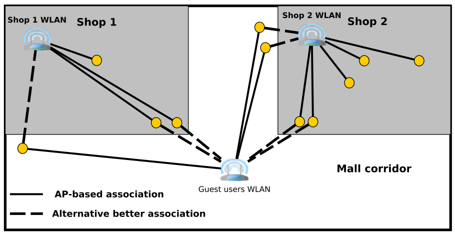

Fig. 1. User association to APs based on service type and network conditions

To obtain this mutual benefit, the APs of both the mall and the shops should be able to work in a synergistic fashion offering part of their resources for users of other types with the goal of enhancing the overall user experience. This idea is not new and in fact is already being used in some public settings, with services like Fon [11] and BT Wi-Fi [12], which allow Internet access via private home WiFi access points for guest users in the neighborhood in return for the same favor for AP owners when they are away from home. However, such solutions do not offer a coordinated management of participating access points for an improved utilization of resources, while prioritization of AP owners with respect to guest users is achieved by separating them on different SSIDs, which degrades the user experience especially in public places where users are constantly on the move. Additionally, this feature is not found in enterprise WLANs and home settings, with association becoming a more difficult problem that needs to take into consideration not only the network status, but also the ever-changing roles of the roaming users.

Based on the aforementioned observations we believe that, similarly to enterprise and home settings, the enhanced coordination capabilities enabled by the centralized network view offered by SDN and its ability to programmatically modify the network's behavior can lead to an improved Quality of Experience (QoE) for public WLAN users and therefore in an increased customer satisfaction (which is normally the purpose of a public WLAN). However, the requirements of premium location-based services, dynamic role changes of users and the provision of differentiated services make public WLANs different from other WLAN settings. Our proposed SDN management framework for public WLANs, VALI, aims to meet these unique requirements.

III. Related Work

Several solutions have been proposed for WLAN management, mostly focusing on enterprise or home WLAN settings. These solutions span both the SDN and non-SDN literature and attempt to solve a number of issues that WLANs are faced with. In the non-SDN domain, most works target the enterprise. We briefly outline a few examples here. In [13], authors attempt to mitigate interference by using centralized packet scheduling where a packet is scheduled for transmission only if there are no interfering links. PIE [14] is another example of a centralized interference management system that aims to eliminate both sender and receiver-side interference.

To achieve this, it uses a controller to process the transmission statistics from APs in order to validate the transmissions and detect any interfering links, mitigating interference by controlling the packet scheduling, dynamic channel assignments and transmission power of APs. DAIR [15] is a framework for managing and monitoring enterprise WLANs by taking advantage of the extensively deployed wired networks and the desktop machines of enterprise settings, by attaching to them WiFi dongles that allow them to monitor the wireless traffic.

Apart from the aforementioned frameworks and tools, a number of SDN-based solutions have also appeared in the literature recently. Odin [7] is a centralized management framework targeting the enterprise. Odin simplifies the management of wireless clients by allowing a logically centralized controller to manage their association to physical access points through the abstraction of a Lightweight Virtual Access Point (LVAP). OpenSDWN [16] takes this further with an SDN management framework that provides customized services to clients through client-specific middleboxes and LVAPs that maintain client transmission properties and association state information. On the other hand, Coap [8] is a representative SDN-based interference management framework for home WLANs which allows the coordination, configuration and management of several home APs through an open API. But none of the existing solutions meet the distinct additional requirements of public WLANs for premium location-based services, dynamic role changes of users and provision of differentiated services, which motivates our work.

IV. VALI FRAMEWORK

A. Overview

As already discussed in Section II, the environment in which VALI is expected to operate is a public setting consisting of several WiFi APs deployed either by shop owners or by other management entities like for instance the central mall management. In the simplest case all APs could share the same connection to the Internet, but some shop owners could also choose to use their own connection, which would allow them to provide an even better or even exclusive service to their respective customers.

In all cases, we envision a setting where shop owners would allow their APs to be managed by a central controller through the installation of an agent. Moreover they would agree to give part of their resources to be used by the controller for other purposes, e.g. for allowing access to guest users or to users of neighboring shops. This could be done by signing a contract that would designate the amount of resources to be shared and the type of services that the controller is expected to provide to actual shop customers in contrast to simple guests, e.g. access to a private network like a digital library or an online music store for free music previews. The incentive for agreeing to participate in such a setting would be the need to improve the overall quality of experience of the public WLAN users (both shop customers and simple guests), since this could mutually benefit all the participating entities of the WLAN as explained in Section II.

B. System Architecture

The architecture of VALI is illustrated in Figure 2. As already mentioned, the system consists of a number of APs, each running an agent and communicating with the VALI controller. The controller and management applications residing above it are responsible for maintaining a logically centralized view of the network and for programmatically managing the association of users to APs and the establishment of traffic rules according to the policies defined by the entities participating in the public WLAN. On the other hand, the agents of the APs are responsible for handling time critical MAC operations, for gathering statistics and responding to queries of the controller and for enforcing the association decisions made by the controller for the clients.

In order for VALI to control the network data plane, it employs mechanisms both for the wired and the wireless domain. For the wired part VALI employs the OpenFlow protocol to manipulate the flows of users based on the decisions made by the controller. For the wireless part it leverages the concept of a Lightweight Virtual Access Point (LVAP) to provide an abstraction over user association. The way it does this is by creating a unique BSSID for each client upon association, instead of all the clients using the same one. This allows the infrastructure to take control over user association and mobility management simply by performing a context transfer of the LVAPs from one AP to another. The idea of the LVAP was first introduced by the Odin framework [7], however VALI extends it in order to deal with the new requirements of dynamic user prioritization and bandwidth allocation.

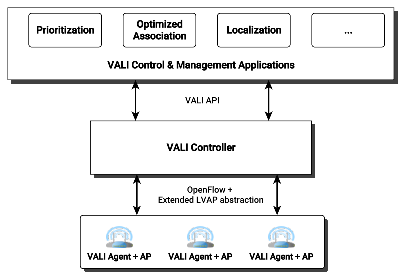

Fig. 2. VALI System Architecture

VALI employs a few key elements for the effective management of public WLANs. As already discussed in Section II, public networks are characterized by the need to provide differentiated services to users based on their location, while also guaranteeing optimal performance based on the underlying network conditions and the users' physical association to APs. For these reasons, VALI identifies three key management applications (Figure 2), i.e. Localization, Optimized Association and Prioritization, running on top of the controller. We argue that these applications enable integral operations that any framework targeting public WLANs should inherently support.

Localization This application is used to dynamically differentiate and categorize users in the public WLAN setting. Using its location a client's LVAP is properly tagged based on its current role. For instance, in the mall example discussed in Section II, the localization module would tag a client walking in the open area of the mall as a guest user, while a client located in a shop would be tagged as a shop customer. The role that a client assumes can change dynamically as the user roams the area of the public WLAN and is defined based on the agreement made between the AP owner and the management authority. For instance, one shop in the mall could perceive as customers only those that are located in the bounds of the shop for more than a few minutes, while another shop could accept as its customers clients that are within a couple of meters from the shop.

Optimized Association This application provides an association configuration, similar to the one illustrated in Figure 1 in order to achieve a high overall network performance (in terms of throughput and fairness). While choosing the optimal configuration, the module considers parameters such as the network topology, the role of a user (user priority), the air time utilization of different QoS service classes and the amount of resources that the APs can provide for different types of users. A map is then constructed with the possible APs that a user can associate with at any point in time based on its location. Finally, the optimized association application migrates users across different APs simply by transferring the proper LVAP.

Prioritization This application is used in order to provide differentiated services to clients based on their current role, as discussed in Section II. More specifically, the module observes the tag assigned to a client's LVAP by the Localization module and imposes priority, bandwidth and access limitations on each AP. To do this, it communicates with the agents running on the access points and informs them on the changes that they need to perform in traffic rules relevant to each user.

The communication of the aforementioned applications with the VALI controller is achieved through an open API (VALI API), which essentially allows them to be developed and modified programmatically based on the policies and algorithms selected for a specific public space setting. This means that VALI is an SDN-based framework for public WLANs that identifies *what* functions need to be supported by the controller, while allowing the management entities decide *how* these functions should be implemented. For example, VALI indicates that all users associated to a network managed by it should be tagged with a role based on their location, but it does not specify the exact conditions that will give the user that role (e.g. specific proximity of a user to a location or time that a user stayed in that location). Apart from the aforementioned core applications, the VALI API could be extended to be used for the development of a number of useful applications in the context of public WLAN settings, like for instance applications for analytics and for ads (e.g. based on a user's traffic and mobility pattern within the public space).

V. Implementation

In order to demonstrate the applicability and the benefits of our solution we created a prototype implementation of VALI which is described in this section.

A. Master Controller, Agents and LVAPs

As already discussed, the LVAP abstraction was first introduced in the Odin framework [7], and therefore Odin was a reasonable choice to form the basis of our own controller. However, since Odin was designed to target enterprise networks, it lacked the localization and user differentiation features required for VALI. For this reason, we extended the LVAP abstraction to also include an additional *tag* element, which would describe the role of a client based on its current location and would be used by the controller for its association and prioritization operations.

The master controller was implemented using the Java-based Floodlight OpenFlow controller with the Odin framework and the localization-enhanced LVAP abstraction enabled. AP agents were also based on the agents provided by the Odin framework for OpenWRT-based access points running Click for modular routers, but were extended to support the new requirements of localization and prioritization. Odin was also extended to support messages specific to VALI, like messages for changing a client's role and messages for enforcing bandwidth limitations to clients based on their location and their current role. The OpenFlow protocol was used for configuring the forwarding tables of the APs taking into consideration the tag of a client's LVAP for determining the proper flow rules. Finally, the management of LVAPs was performed using ODIN specific commands.

B. VALI Management Applications

Using the VALI API we implemented the localization, prioritization and optimal user association applications required by the VALI management framework. As already discussed in Section IV-B, these applications are implementation-specific and could be replaced with other solutions, leading to a more sophisticated management framework. Therefore, the algorithms, policies and techniques that we chose for our proof-of-concept are only indicative of the capabilities of VALI.

1) Localization application: For this application we used a simple coarse grained zone level localization mechanism that employs RSSI-based WiFi fingerprints for identifying clients' locations. The application has access to a localization database and an ENVI server. The localization database is used to store WiFi fingerprints collected from various locations within the public WLAN during a training phase, while the ENVI server stores the WiFi fingerprints of the associated clients. The application runs periodically and parses the fingerprints of the clients in the ENVI server comparing them against the data of the localization database. A closest match is found by calculating the Euclidean distance between the fingerprint of the client and the fingerprints stored in the database, similar to the methodology described in [17] and [18]. If the results of this process show that a client has moved to a different location, the application dynamically changes the state of the client's LVAP, by changing the value of its tag entry, e.g., switch from a guest mall user to a customer of the bookshop.

2) Optimized Association Application: In our implementation, the initial association decision is left to the client and is normally based on RSSI. Once a client is associated to an AP, a new LVAP is created and assigned to it. The optimized association application has access to the same ENVI server as the localization application, which it uses to analyze WiFi fingerprints uploaded by the various clients to determine the possible APs a client can associate with. The application also estimates possible data rates in each case and runs the user association algorithm proposed in [19], which takes as input the aforementioned parameters, along with the role that each client has based on its location tag and the available resources per class in each AP and solves an optimization problem that gives the best set of associations. The controller then enforces these associations by performing the required LVAP handoffs.

3) Prioritization Application: Service prioritization for clients was implemented by using a Linux-based tool called TC which offers many scheduling algorithms to shape network traffic. The specific scheduler that we chose is called Hierarchy Token Bucket (HTB) and is used to provide class based priority, where unused resources of a class get evenly distributed among the other clients. The application assigns a user to a specific scheduling class based on its current role that is designated by the tag field of the LVAP. In each AP, one class receives the majority of the resources, while the rest of the classes only get a small portion based on the agreement between the management entity and the AP owner. The number of classes and the allocation schemes used could be modified according on the specific usage scenario in which VALI is deployed.

VI. Evaluation

In this section, we present our evaluation results for VALI. Our main focus was in assessing the benefit with the three management modules presented in Section IV enabled and the utility that these can provide for an improved user experience in public WLAN settings. In order to perform our experiments we built a prototype testbed managed by the VALI framework with the management modules implemented in the way described in Section V. Our testbed consisted of three APs and twelve heterogeneous clients (smartphones and tablets) operating in infrastructure mode. The master controller and the management applications were deployed in a commodity desktop along with the ENVI server and the localization database.

The testbed was deployed on a part of the first floor of the Informatics Forum building at the University of Edinburgh, which is composed of a number of offices, labs and common spaces laid in the floorplan that is illustrated in Figure 3 and closely resembles that of a real public WLAN deployment like that of a shopping center. We defined two types of zones for user access, one High Priority (HP) representing shop spaces and one Low Priority (LP) for common space areas and we assigned each room of the region under study into one of these zones. Similarly each AP was dedicated to a specific zone type (HP or LP) with the majority of their resources assigned to serve users of that type. The remaining resources were available to be used by the controller in order to serve clients of the other type. For our evaluation, these zones were meant to reflect the type of QoS that a client expects once it enters in their region regardless of the client's association with a specific AP. However, it should be noted that in more complicated scenarios, each zone could also translate to a different set of flow rules or premium user services. Moreover, we could also define additional zones, e.g. a different zone for each room, however we chose to use only two zones to keep the scenario simple.

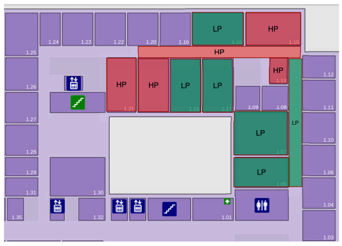

Fig. 3. Floorplan of testbed setup

An integral part of VALI is its ability to perform localization of clients. For this reason and based on the way that the localization module was implemented (Section V) we created a localization database by gathering 1000 WiFi fingerprints from various places within the region of interest. The measurements were taken during office hours, since this period is usually busy with a lot of staff and students walking by, effectively mimicking a public area. After building the database, we evaluated the effectiveness of the localization module by tagging a diverse set of clients in 130 unique test locations across the testbed area. We compared the LVAP location tag given by the module to a client with the ground truth zone that the client belongs to. From the confusion matrix results shown in Table I, we can observe that the localization module assigns clients to the proper zones correctly most of the time, which demonstrates that coarse grained zone level localization of clients is fairly easy to achieve even with a simple localization scheme like the one employed here and therefore makes the use of such a framework applicable and appealing in realistic scenarios.

Actual Priority Zone	Inferred Priority Zone	
	HP Zone	LP Zone
HP Zone	45	11
LP Zone	12	62

TABLE I
Categorization Accuracy

The next thing that we wanted to demonstrate is the effect of our framework in providing location based prioritized services. To do this, we compared our solution against a static traffic-based prioritization method like the one provided by Odin, where a client is statically assigned a role and type of service based on its id. For our experiment we used a single client starting from an LP zone and moving towards an HP zone while generating TCP traffic using iperf. Here we assume that the prioritized service in an HP zone comes in the form of an increased throughput, but as already discussed it could also be translated into a different set of traffic rules etc. As it can be seen in Figure 4, during the second minute the client goes from an LP to an HP zone. We can observe that with localization enabled, the client's throughput doubles, meaning that the user obtained the premium service that it expected automatically without performing any additional actions like manually choosing the new zone's SSID. On the other hand, without localization the client's service remains unchanged unless the user chooses to manually switch to the AP of a different zone.

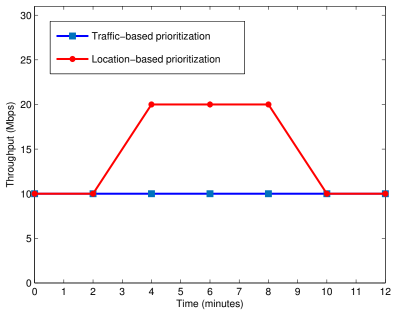

Fig. 4. Location-based prioritization Vs Traffic-based prioritization

The final thing that we evaluated was how the optimized association employed by VALI can offer a better utilization of resources, while taking into consideration the constraints of the client's expected type of service and the amount of resources that can be shared for different types of users. To achieve this we set two of the APs in LP zones and one AP in an HP zone and we set 20% of the resources of both types of APs to be shared with clients of other types, resembling the contract agreement that shop owners could sign with the mall management entity. This means that 20% of the resources in an HP AP could be allocated to LP clients that are close to an HP-LP border region and vice versa. The idea of the experiment was to move devices from the LP zones to the HP zone and observe how this would affect the overall throughput of clients obtaining the HP service. As a baseline, we used an association scheme that allows the association of clients only to the AP with the highest RSSI with the constraint that this AP also belongs to the designated zone, meaning that clients entering the HP zone would only be able to associate with an HP AP and vice versa.

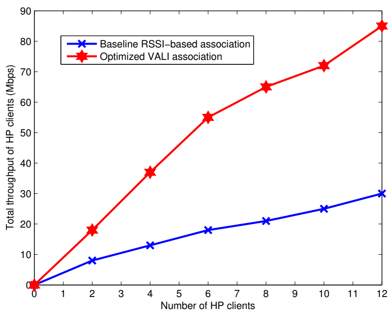

Fig. 5. Optimized Association vs RSSI-based association

The client devices were initially placed in LP zones close to their common borders with the HP zone and generated TCP traffic using iperf. We began the experiment by forcing all the clients to associate with the access points of LP zones similarly to how most mall guests would initiate their association with the network while entering the common areas of the mall. We would then move each one of the devices from the LP zone to the HP zone, making the VALI controller to dynamically switch their role from LP to HP devices. As we can see in Figure 5, as more devices switched from an LP to an HP zone the overall throughput of HP devices increased in both cases, which is something to be expected. However, we can also observe that the rate of increase in the baseline case is much lower than that of the optimized association case. The reason for this is that in the baseline case the controller chose to associate all HP clients to the HP AP, while in the case of the optimized association, some of the HP clients were associated with the LP APs even once they entered the HP zone, by exploiting the shared resources that the LP APs offered. This led to a higher total throughput, while the controller allowed all the devices to still use the premium services offered by the HP zone.

VII. Conclusion

In this paper we identified the unique characteristics of public WLANs and explained why management solutions targeting the home and enterprise settings are inadequate. This led us to create VALI, an SDN framework for the management of public WLAN settings. VALI builds on top of the lightweight virtual access point abstraction of Odin, but extends it to support location-aware services, prioritization and optimized association. We consider the shopping mall scenario as a specific use case to present how VALI framework can address the distinct requirements posed by public WLAN settings. We implemented and evaluated VALI in a real prototype testbed, with the results demonstrating the benefits that such a framework could offer.

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