A Longitudinal Study of Pervasive Display Personalisation

MATEUSZ MIKUSZ, Lancaster University
PETER SHAW, Lancaster University
NIGEL DAVIES, Lancaster University
PETTERI NURMI, University of Helsinki
SARAH CLINCH, University of Manchester
LUDWIG TROTTER, Lancaster University
IVAN ELHART, Università della Svizzera italiana (USI)
MARC LANGHEINRICH, Università della Svizzera italiana (USI)
ADRIAN FRIDAY, Lancaster University

Widespread sensing devices enable a world in which physical spaces become personalised in the presence of mobile users. An important example of such personalisation is the use of pervasive displays to show content that matches the requirements of proximate viewers. Despite prior work on prototype systems that use mobile devices to personalise displays, no significant attempts to trial such systems have been carried out. In this paper we report on our experiences of designing, developing and operating the world's first comprehensive display personalisation service for mobile users. Through a set of rigorous quantitative measures and eleven potential user/stakeholder interviews, we demonstrate the success of the platform in realising display personalisation, and offer a series of reflections to inform the design of future systems.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing**; **Ubiquitous and mobile computing systems and tools**.

Additional Key Words and Phrases: mobile computing, smart environments, location-based applications, pervasive displays

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1 INTRODUCTION

Pervasive displays, such as digital signage, are becoming increasingly ubiquitous in our built environment. Estimates suggest that over 45 million digital signs have been deployed globally [58].

Authors' addresses: Mateusz Mikusz, Lancaster University, InfoLab21, Lancaster, U.K., LA1 4WA, m.mikusz@lancaster.ac.uk; Peter Shaw, Lancaster University, InfoLab21, Lancaster, U.K., LA1 4WA, p.shaw@lancaster.ac.uk; Nigel Davies, Lancaster University, InfoLab21, Lancaster, U.K., LA1 4WA, n.a.davies@lancaster.ac.uk; Petteri Nurmi, University of Helsinki, InfoLab21, Lancaster, U.K., LA1 4WA, p.nurmi@lancaster.ac.uk; Sarah Clinch, University of Manchester, Manchester, U.K., M13 9PL, sarah.clinch@manchester.ac.uk; Ludwig Trotter, Lancaster University, InfoLab21, Lancaster, U.K., LA1 4WA, l.trotter@lancaster.ac.uk; Ivan Elhart, Università della Svizzera italiana (USI), Lugano, Switzerland, 6900, ivan.elhart@usi.ch; Marc Langheinrich, Università della Svizzera italiana (USI), Lugano, Switzerland, 6900, marc.langheinrich@usi.ch; Adrian Friday, Lancaster University, InfoLab21, Lancaster, U.K., LA1 4WA, a.friday@lancaster.ac.uk.

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Despite their ubiquity, there is little evidence that such displays are an effective way of communicating with potential viewers. Indeed, systematic observations of viewer behaviour in the proximity of digital signs suggest that viewers exhibit a phenomenon known as *display blindness* – choosing to ignore public displays because they perceive them as having little content of relevance [34, 41].

Since the mid nineties, researchers have attempted to address display blindness by enabling content to be *tailored* or *personalised* to viewers within close proximity [18]. A popular approach has been to use mobile phones for detecting potential viewers' proximity to a screen (e.g., using Bluetooth) and to tailor the screen's content according to the individuals in front of them [15, 28, 29, 39]. Within commercial settings, another common practice adjusts content based on coarse-grained audience demographics captured through video analytics [27]. However, to date few attempts have been made at deploying and evaluating display personalisation systems in real-world settings. As a result, limited information exists about best practices to follow, potential pitfalls that need to be avoided when deploying display personalisation systems and long-term use of this personalisation technology. Understanding these factors is fundamental to improving the effectiveness of personalised pervasive displays in long-term use, and identifying key open research areas.

This paper contributes by rigorously investigating issues surrounding field deployments of personalised pervasive displays and draws on our experiences of instantiating display personalisation *as a service* (c.f. a controlled experiment) on a large university campus. We report data from an ongoing deployment at Lancaster University, with detailed analysis of a period of 165 days during which time we supported $24,673$ requests for personalised content across 44 displays, allowing us to report longitudinal experiences of supporting display personalisation at scale. Our deployment relies on the Tacita architectural model proposed by Davies et al. [15], which we extend to support our large-scale field trials. Where possible, we contrast our findings with those obtained from controlled laboratory studies, highlighting key discrepancies between real world deployments and the controlled laboratory tests. Our key contributions are:

Firstly, we provide the community's first robust analysis of how viewers use display personalisation systems in real-world settings. We draw on measurements collected from our deployment at Lancaster University and analyse content requests made by users during the deployment. Analysing the distribution of requests across content categories, and spatio-temporal patterns across the campus environment, allows an evidenced investigation of whether people use display personalisation and, if they do, what exactly they choose to see on the displays. Our results show that people are indeed willing to exploit display personalisation to provide easy access to relevant factual information (e.g. real-time transport updates) while rejecting the use of displays for content such as social media. We also examine the level of engagement users have with our system by looking at the persistence of content requests over time. Our results indicate that initially our display personalisation system can indeed reach a high conversion rate, but that the level of engagement starts to dwindle significantly over time. In particular, only 40% of users continue issuing content requests after three weeks. We further highlight the challenges deployments face in collecting long-term usage data in the absence of reliable sources of information on content activation, and provide detailed insights regarding the long-term maintenance of a user base. There have been no previously published studies of how viewers use display personalisation systems in real-world settings.

Secondly, we examine the adequacy of a commercial state-of-the-art indoor location tracking technology based on Bluetooth Low Energy beacons (iBeacon) to support timely personalisation of displays for viewers. Using a combination of data collected from our deployments and controlled small-scale trials conducted in a laboratory setting we demonstrate that current commercial technologies can detect entry to display regions with reasonable accuracy, but they are poor at estimating when a user leaves the region and hence how long the user spent in the vicinity of a display. We also show that the accuracy of exit detection can be improved using custom ranging techniques, but even in such cases the performance is sensitive to the configuration of the proximity detection technologies and the nature of the deployment environment. These findings are important because they impact on multiple uses of BLE including the perceived reliability of location-based display analytics and metrics that are used to gauge the success (or failure) of specific display campaigns. They also represent a significant advance of prior studies which have not considered the use of ranging techniques and have focused on observing performance in single installations.

Thirdly, we report on the results of a series of structured interviews designed to elicit viewers' expectations and attitudes together with those of stakeholders responsible for providing content. We found that most viewers were positive about display personalisation despite privacy concerns. Content creators appear to see increasing value in display personalisation, especially in terms of using displays to reach specific groups of viewers and we did not observe the same concerns regarding the need to identify and potentially moderate personalisation requests that were reported by Clinch et al. [11] – thus representing a significant change in our understanding of attitudes to personalisation.

Finally, we reflect on our experiences and findings, providing insights for future deployments and highlighting open research challenges. We specifically highlight changes that are required to the reported state-of-the-art in personalisation architectures in order to support long-term deployments at scale.

2 RELATED WORK

There is a rich history of research into pervasive displays dating back to the 1980s [13]. This research includes a multitude of focal areas including, for example, display hardware, interaction modalities and audience behaviour. For the purposes of this paper, we concern ourselves only with prior work relating to deployments of pervasive displays and with display personalisation.

2.1 Long-Lived Pervasive Display Deployments

Early research into display deployments explored their use as 'media links', i.e. using video and audio links to connect together physically separate spaces. For example, Kit Galloway and Sherrie Rabinowitz created the "Hole-In-Space" [21], a three day art installation in November 1980. The installation featured two large back-projected displays (plus speakers and cameras) installed in sidewalk-facing windows of the Lincoln Center for the Performing Arts in New York City and "The Broadway" department store in Los Angeles. A satellite link between the two cities allowed the creation of virtual windows in which the video feed of New York was shown on the screen in L.A. and the video from L.A. in New York. Displays providing media links were also deployed in (research) workplace settings. The Xerox PARC Media Spaces [7, 23] connected researchers at sites in Palo Alto and Portland by providing steerable video and audio links in the "common area" of each site. The media links ran 24 hours a day, seven days a week for over two years, finishing only when the offices in Portland closed. Whilst originally intended to support formal meetings, the majority of interactions over the links were chance encounters lasting for less than five minutes. A similar system at Bellcore Labs, the VideoWindow [19], connected researchers on two different floors of the building using large projected displays in common areas.

Pervasive display research has often involved deployments to help explore user behaviour outside the laboratory. Much of the early research into display deployments focused on urban environments, e.g. "CityWall" [47] that consisted of a touch-enabled display situated in a city centre that showed content relevant to the context of the deployment, e.g. images and videos tagged with the location. Viewers were able to use both gestures and touch interaction to reorder and scale media items shown on the display. Deploying displays in urban spaces to improve engagement within a community has also been explored by Schroeter et al. [50] who conducted a set of deployments of interactive displays at bus stops, museums and conferences. Taylor et al. [56] utilised interactive public displays as a way of providing situated voting devices for communities; a two-month deployment led to the identification of a set of guidelines specific to the design of democracy tools. A larger research-based deployment of public displays was conducted by José et al. [29] who placed a total of 10 displays in various locations including a university, schools and cafes. The authors deployed a set of applications and content, investigating how user-generated content can improve the use of situated displays in urban settings. A university deployment was also used by Greis et al. [25], whose three displays were used to investigate the impact of delays in the moderation of user-generated content, i.e. the time between the submission of a content item and the time at which the content appeared on the screen.

Beyond urban environments, Taylor and Cheverst [55] deployed the "Wray Photo Display", a digital display in a rural village. The deployment consisted of a small number of interactive touch-enabled displays deployed in key locations within the village including a bookshop and the village hall. The displays allowed residents to access photos of recent events, information about events in the future, and to use Bluetooth to upload custom content for other members of the community. An extended deployment allowed researchers to explore which content their community of viewers shared and viewed.

One of the largest research-based deployments of pervasive displays was the UBI-Hotspots system, a network of interactive touch-enabled displays located across the city centre of Oulu, Finland [43]. The deployment consisted of up to twelve in- and outdoor displays and served as a platform for research into pervasive computing and human computer interaction. UBI-Hotspots provided easy deployment of web-based display applications to the entire display network which become immediately accessible by pedestrians and passers-by. In addition to touch-based interaction, UBI-Hotspots also supported a level of explicit personalisation – users were able to register and authenticate themselves at the display via an RFID tag and, for example, participate in games, post messages to bulletin boards, and retrieve information such as bus departure times. Whilst UBI-Hotspots was one of the longest running research-based deployments, the number of displays has gradually reduced and the system has now been decommissioned [26].

Large-scale 'in-the-wild' deployments of public displays (both in terms of number of displays and physical size of individual displays) are more common as part of commercial display networks and are typically driven by commercial entities such as advertisement companies. For example, LinkNYC[1] is a recent example of a large-scale public display deployment across New York City in which old telephone boxes have been transformed to modern, interaction-enabled public display kiosks delivering adverts and allowing passers-by to access city-related services and directions. The deployment consists of, to date, over 7,500 displays and has started to expand to other cities such as London (branded as LinkUK[2]). Previous commercial display deployments include the BBC Big Screen featuring large display installations situated in over 21 cities across the U.K. to show major events. Neither LinkNYC, LinkLondon, nor BBC Big Screens attempted to offer personalised content, but were part of generalised attempts to "transform our urban environments" [31].

Our research builds on the e-Campus infrastructure [20], the world's largest research-focussed display network, currently consisting of over 85 displays situated across the campus at Lancaster University. Whilst the initial e-Campus infrastructure consisted of a set of displays showing largely

[1] https://www.link.nyc
[2] https://www.inlinkuk.com

static content (e.g. slideshows), the network and functionality has since been substantially extended. We describe e-Campus and relevant extensions in subsequent sections of this paper.

2.2 Display Personalisation

While the falling cost of hardware and the difficulty of reaching the general public through fragmented conventional media has led to the deployment of increasing numbers of public display systems, the vast majority of today's public displays effectively disappear: people have become so accustomed to their low utility that they have become highly skilled at ignoring them [34, 41]. One approach to tackling this problem is the introduction of personalised content. Our previous explorations in this domain led to the identification of three distinct classes of display personalisation [15]:

Walk-by personalisation in which viewers passing by a single display see content that is relevant to them (as exemplified in the 2002 film Minority Report in which the characters are subject to personalised adverts as they journey across the city).

Longitudinal personalisation in which viewer preferences for personalised content are realised as a shift in content on multiple screens in a given geographic area, accommodating preferences from multiple viewers, typically over an extended period of time. In practical terms this might mean, e.g., that the content shown on the displays at a university campus automatically changes during vacation time or that content in a shopping mall adjusts during weekends or school holidays.

Active personalisation in which users (inter-)actively engage with a display system to control personalised applications on a nearby display, e.g. to extend a mobile phone display for better viewing of complex data.

The selection of appropriate content may be based either on *explicit* user preferences (as in [15, 18, 43] or determined *implicitly* based on contextual information about the viewer (or group of viewers) currently present in front of a display [36]. In this paper we focus on explicit user preferences to determine content personalisation.

The idea of explicitly personalising public displays as users walk by was first suggested by Finney et al. [18], who used Active Badges to trigger personalised content such as unread email messages on nearby displays. Russell and Gossweiler [49] investigated the use of public displays for the delivery of personalised content in combination with an appropriate way to identify and authenticate the viewer. Their work was one of the early examples to support 'walk-up personalisation' (in contrast to walk by) due to the requirement to explicitly interact and request personalised content by walking up to the display to authenticate. Other systems have used IR [33], RFID tags [48], or custom-built wireless devices [57] for proximity detection. Several systems have explored offering more explicit control in display personalisation. For example, InstantPlaces [28] allowed users to send pictures to a portion of the display allocated to their device, whilst e-Campus [14] and BlueTone [16] allowed viewers to take control of the display for one of a number of predefined applications using Bluetooth. A more indirect form of personalisation was proposed by Müller and Krüger [40] in which the system estimates viewers' paths between displays to coordinate content across multiple displays. Greenberg et al.'s *proxemic interactions* [24] use vision-based motion capture to track users' paths, feeding this information to a display app that can thus continuously adapt its output. A simpler adaptation is used by Tafreshi et al. [52], who proposed a responsive design approach to public display applications that takes viewer distances and numbers into account.

In addition to proximity, public displays can also be personalised based on the user's absolute location or spatial orientation. AT&T Cambridge's classic "Sentient Computing" project [2] used

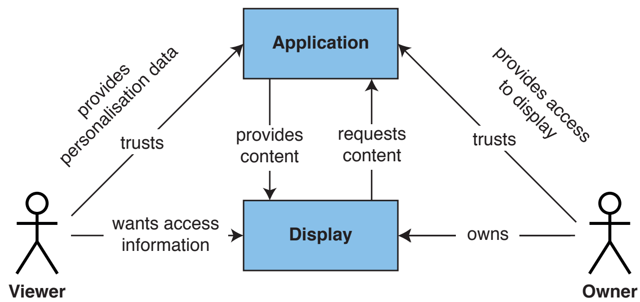


Fig. 1. Trust relationships in Tacita, adapted from [15].

data from an infrastructure-based location tracking technology (the "bat") to create a world model that included support for containment of a "user's zone" inside a "display's zone" and enabled applications including proximity based logins and "teleporting" in which a user was able to migrate that their virtual desktop to a physically close machine.

In many systems content to be displayed as a result of personalisation simply replaces (or is interleaved with) existing signage content but other options are possible. Parker et al. [45] created a mobile augmented reality application that allowed passers-by to access personalised content on a public display via their mobile phone screen. The authors motivated their approach in terms of the privacy concerns arising as a result of showing personal content on a public display. Using a smaller screen visible only to the passers-by they argued can help address some of these privacy-related issues. In addition to a focus on privacy, the authors further identified a set of key issues for personalisation including: the importance of timely information, the need to take account of potential issues arising from multiple passers-by interacting with a public display and, the need to ensure user familiarity with design modalities and interaction workflows. Using a similar system, Baldauf et al. developed "the augmented video wall" [6] allowing viewers to retrieve personalised and individual media content from a public display through a dedicated mobile phone applications. Viewers could point their mobile phone at a public display and see their persoanlised content on their mobile phone screen.

Ostkamp et al. [44] investigated issues regarding the delivery of multiple pieces of (targeted) content on a single public display by applying visual multiplexing techniques. The approach developed by the author relies on a mobile device employed to demultiplex content shown on a public display. Related to the work conducted by Parker et al. [45], viewers are required to point their mobile phone at a public display to retrieve the content relevant for their preferences (e.g. allowing the mobile phone to extract the multiplexed content). In the context of display personalisation, content multiplexing can be one solution to address potential issues of conflicting content requests that can emerge if multiple viewers request different pieces of content on the same display.

The most recent significant new approach to display personalisation is our own Tacita system, first reported in Davies et al. [15]. Tacita's underlying premise is the trust model illustrated in Figure 1; viewers issue content requests to cloud-based content providers with which they already have an established trust relationship (e.g. BBC World Service, Facebook) while display owners only honour requests for screen real estate from similarly trusted content providers. In this way Tacita is able to provide viewers with privacy protection (there is no way for the owner of a display network to identify individual users making requests, nor is it possible for them to produce traces of individual mobility patterns) while simultaneously reassuring display owners that they are able to maintain control over the content shown on their screens since they only honour requests for screen real estate from trusted content providers. The current paper builds on Tacita's architecture for anonymous personalisation of pervasive displays by mobile users.

Davies et al.'s [15] Tacita architecture is comprised of four components:

Personalisable Applications Content providers that are trusted by both users and screen owners to supply content for public displays in response to requests from users.

Public Displays Shared screens that can display content in response to requests from viewers. Displays announce lists of acceptable content providers to nearby mobile users.

Map Providers Services that supply lists of displays and their locations, plus the locations within which users must be situated to generate content requests (trigger zones) and the content providers from which the displays will accept content. These lists are collated in the form of "maps".

Mobile Clients A mobile application that (i) allows viewers to specify preferences for display personalisation and, (ii) detects if the user is in the proximity of a public display, sending a notification to the appropriate content providers when a user and display are proximate.

After downloading the Tacita Mobile Client, the user's mobile application builds a list of nearby displays and their personalisation options – either by listening to announcements from the the displays or by connecting to an appropriate map provider. After new content providers have been discovered, the user can activate and configure them through the Tacita Mobile Client and provide their preferences (both global preferences such as their preferred language, and preferences for specific content providers such as the name of their favourite team to enable personalisation of sports news). The user's location is monitored within the mobile application in order to detect if a user has entered the trigger zone of a public display. Unlike preceding solutions, entry into a trigger zone leads not to direct request to the display (or associated infrastructure), but to a request from the user to their trusted content provider. This provided then requests screen real estate on the user's behalf – allowing displays to be personalised without revealing the location or device ID of any individual user.

2.3 Analysis of Related Work

Despite widespread commercial deployments, and a sustained history of research activity, there are still remarkably few long-lived pervasive display deployments from which researchers have been able to build a body of understanding. Real-world commercial platforms are often large in scale and persist over time, but offer little in the way of options for personalisation. By contrast, research systems have experimented with display personalisation for over twenty years [18], but the average duration of any display system (with and without personalisation) is of the order of days or weeks rather than months. With few extended deployments, studies of user behaviour can say little about the ongoing response to pervasive displays and the content that they provide. The present work contributes into this space and is differentiated from prior work by:

- *Providing the world's largest and longest deployment of a display personalisation service.* This paper reports data from 165 days across 44 displays, representing the first attempt to explore the viability of display personalisation at scale. Deployed within the context of e-Campus, an established research testbed of almost fifteen years, our display personalisation service is able to achieve longevity (its availability is ongoing) and avoid many of the novelty effects seen when researchers are required to deploy completely new display infrastructure in order to explore its personalisation.
- *Utilising both qualitative and quantitative data to provide a detailed understanding of user behaviour and experiences.* We applied a mixed methods approach conducting a quantitative analysis of our long-term in-the-wild deployment and additional interviews with display

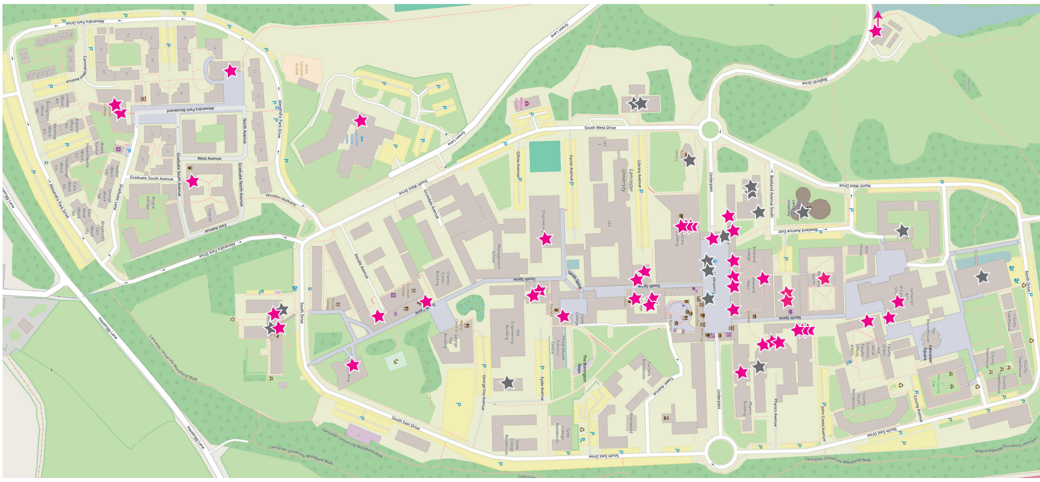


Fig. 2. Map of the *e-Campus* Display Deployment at Lancaster University showing the 65 displays that were in-situ at the beginning of our Tacita deployment and trial (the network has since grown by a further 20 displays). A total of 44 Tacita-enabled displays are represented by pink markers (some overlap means the number of markers is slightly lower than the number of displays); grey markers represent displays that were not Tacita-enabled. A further 4 displays are not represented on the map due to their location off-site (e.g. at a city centre bus station).

stakeholders including content providers (who have years of experience in working with the display network on the university campus) as well as potential end-users of Tacita (including students and staff).

- *Providing a general architecture for personalisation that supports the deployment of arbitrary content channels each handling content personalisation in their own manner.* Instead of developing a single personalisable application to enable our long-term capture of user experiences, we developed a framework that supports arbitrary content providers that can be deployed in an independent manner by display network operators and other stakeholders. Additional personalisable content can be made available over time using our framework, and the architecture can be applied to support other deployment sites in the future.
- *Providing a practical, privacy-preserving mid-point between traditional beaconing architectures and recently proposed trust architectures.* The Tacita system developed in the context of this work has been designed with privacy in mind. Sensitive location traces (in the form of display sightings) and personalisation preferences associated with users are only shared with trusted entities (i.e. trusted content providers). Other stakeholders involved in the display network (e.g. display and space owners) are not able to obtain insights into sensitive data without user consent due to the design of our architecture.

3 DEPLOYMENT CONTEXT

In order to conduct an investigation of issues surrounding in-the-wild deployments of personalisable pervasive displays, we deployed Tacita in the context of Lancaster University's *e-Campus*, the world's largest public display research testbed located. The testbed has been in continuous operation since 2005 and now consists of over 85 public displays situated at key locations across the university campus including departmental buildings, lecture theatres, social/community areas, the library and a communal study area, and the main pathway through the university campus (Figure 2). Typically, the displays show a mix of static content (such as slides with departmental or university-wide news), videos, and websites specifically developed to deliver content for public displays. The display schedule and content can be configured by screen owners and content creators through a set of web-based user interfaces (e-Channels [20] and the Mercury App Store [12]).

Display nodes run Yarely, a digital signage player that retrieves display schedules from backend services in the form of Content Descriptor Sets (CDSs), an XML-based format describing content items and their scheduling constraints (e.g. date and time restrictions) [10]. Yarely uses a Lottery Scheduler to determine which piece of content to play from the options specified in the CDS [37]. The entire *e-Campus* platform is instrumented to capture and analyse display events including content changes and user interactions such as on touch-enabled displays [38].

Stakeholders of the *e-Campus* deployment who control and populate displays with content include college administrators, departmental officers, and the university's press office. Potential viewers of the content distributed throughout the display network include 13,115 students (9,500 undergrads and 3,615 postgrads), plus 3,025 administrative and 1,490 academic members of staff at the university campus. Whilst a large number of students live on campus, the majority of students and staff commute (typically by bus).

4 SUPPORTING MOBILE DISPLAY PERSONALISATION AT SCALE

To support the deployment of Tacita for our long-term trials we have redesigned and restructured the original system architecture proposed by Davies et al. [15] (as summarised on page 7 of this paper). The most significant change is the addition of a Display Gateway component described in more detail below.

4.1 Architecture

Our reworked Tacita architecture consists of the following five core components.

Tacita Channels are personalisable applications that are trusted by both users and screen owners to supply content for public displays in response to requests from users. Viewers can access and configure Tacita Channels through a dedicated mobile phone application (the Tacita Mobile Client). In our deployments, Tacita Channels typically serve dynamic Web-based content depending on the preferences of the passer-by and other contextual information such as the location of the display.

Display Gateways provide an interface to a display deployment through which Tacita Channels can make requests for dynamic content personalisation on displays within the deployment. Tacita Channels request the display of personalised content by providing the location, display and content identifiers, allowing the Display Gateway to validate the request and, if successful subsequently forwarding the request to the appropriate display node.

Public Displays act as standard digital signs – showing content according to predefined schedules – but also provide an interface that allows the interruption of such regular schedules in response to requests from the Display Gateway. After receiving a content change request, individual display nodes access the content provided by the requesting Tacita Channel. The actual selection of the content shown and application of personalisation preferences is conducted by the individual Tacita Channel. For example, Tacita Channels can keep track of viewer locations and displays showing content, mapping both display and user and distribute the appropriate piece of content. Each display node includes a unique display identifier as part of the HTTP request for accessing the Tacita Channel's content.

Map Providers serve as repositories of Tacita maps that describe display locations and associated Display Gateways. Maps can be downloaded by the Tacita Mobile Client onto a user's personal device and updated on a regular basis.

Tacita Mobile Clients have two roles. Firstly, they provide a user interface through which viewers can express their display personalisation preferences in terms of a desire to specific Tacita Channels on nearby displays. Secondly, Tacita Mobile Clients are responsible for monitoring users' locations and informing relevant Tacita Channels when the user enters the proximity of a display.

The approach described above differs from the original Tacita system architecture presented by Davies et al. [15] in which the authors proposed an architecture in which third-party applications (Tacita Channels) directly communicated with individual display nodes to request content changes. Whilst two components have received minor tweaks to terminology and function, *we introduce a new core component, the Display Gateway* that provides a public-facing application programming interface for receiving dynamic content scheduling requests originating from Tacita Channels. In attempting to instantiate the original Tacita system in real-world settings it became clear that direct communication between Tacita Channels and Public Displays is not viable for two reasons. Firstly, in practice many displays operate behind behind firewalls that block traffic from external sources. Secondly, the integration of Tacita in its original form requires modifications to every display in a target network such that they can support incoming requests from Tacita Channels. Neither modifying large number of displays nor creating pathways through the firewalls are viable in large established deployments. It is for this reason that we introduce the Display Gateway, a fundamental change to the initial architecture proposed in [15] where individual display nodes were exposed to content requests from third parties. The Display Gateway provides a single point of entry to any given display infrastructure, and provides a way to orchestrate and map content scheduling requests dynamically to the appropriate display node. Furthermore, the Display Gateway provides a layer of abstraction over underlying signage networks such that deployments of Tacita into new networks now only require modification to a single architectural component.

Our experiences of realising Davies et al.'s Tacita architecture [15] indicate that *the initial approach of having trusted applications communicate directly with displays is unlikely to be compatible with the security practices and heterogeneity of established real-world deployments. Introducing network entry points (Display Gateway) allows networks to be Tacita enabled through the addition of a single new component rather than the modification of individual deployed displays.*

4.2 Integration

To deploy Tacita in the *e-Campus* testbed required minor modifications to a number of system components. In its original implementation, our deployed Yarely configuration pulled updates to display schedules at fixed intervals (e.g. once an hour). To support walk-by personalisation, the system was extended to support notifications from the Display Gateway to immediately adjust the content being displayed. To achieve this we implemented a Web socket sensor as part of the "Sensor Management" component within Yarely to enable communication with the Display Gateway. Content change requests from the Display Gateway are issued as event messages consisting of the description of the requesting content or application as a CDS. To effect the required change in content also necessitated extension of Yarely's scheduler – during its content scheduling process Yarely filters content items to produce a minimal set of eligible items, from which one is selected at random using a lottery approach [37]. To support Tacita we implemented an additional filter that identifies if a content item request has been received and whether it corresponds to an item in the display's schedule of approved content items; if so, then the request is honoured immediately. The advantage of using a lottery-based approach is that this can subsequently be extended to support different scheduling policies such as prioritising content that is the subject of multiple requests from different viewers. These changes to Yarely are in addition to the development of an *e-Campus* Display Gateway to support incoming requests from Tacita Channels. Finally, we modified the user interfaces for controlling *e-Campus* to enable display owners and content creators to indicate whether Tacita content should be shown on each display, and whether content they create should be offered to users via Tacita.

Reflecting on our experiences of deploying Tacita within the context of *e-Campus*, we observe that the addition of an Display Gateway did not completely eliminate further software changes, but that *the use of open signage software enabled easy addition of new components to accommodate changes in context provision and scheduling preferences.*

4.3 Localisation and Mapping

Fundamental to the Tacita approach is that all localisation is performed on a user's mobile device and that these devices are also responsible for issuing personalisation requests. This means that mobile devices need to be able to determine when they are in the proximity of displays. To support this, the location and capabilities of displays are encoded in maps that provide detailed information on supported Tacita Channels for each individual display [15].

For our deployment we created a map schema (example map shown in Figure 3). This JSON representation includes *meta*data about the map itself (a text description, publication date, period of validity and version information) that enables future changes to the map structure while maintaining backwards compatibility. The remaining JSON data takes the form of an array of *domains*; each object within the array completely represents the set of hardware within a given display deployment (i.e. managed by a single Display Gateway). When making a content request, the Tacita Mobile Client forwards domain information (the *proxy* URI) to the Tacita Channel, which uses this information to determine the destination for requesting screen real-estate. Each domain contains an array of display *entries* that contains: (i) the geographic locations (*regions*) within which the display can be viewed; the locations or other means by which a user's proximity to the display will be determined (*trigger zones*); and (iii) the enabled Channels available at that display (*capabilities*). Both locations and trigger zones can be expressed as circular regions in the form of latitude/longitude tuples including a radius value, or as proximity descriptions using BLE beacon identifiers. In the current deployment we use BLE beacons for proximity detection – motivated by the widespread support for BLE in modern mobile handsets and the relatively modest energy demands it incurs. The display *capabilities* objects each describe a Tacita Channel, including its *name*, *description* and *icon*, a URI (*config_url*) for the configuration page to be embedded into the Tacita app (see Section 4.4), and the *callback_url* to be used when users enter a relevant trigger zone.

Davies et al. [15] envisaged two mechanisms for the dissemination of maps to the Tacita Mobile Client: announcements (i.e. displays transmitting their capabilities) and map providers (i.e. repositories of maps). While announcements were described as the principle mechanism, map providers were introduced as an optimisation for the case in which displays were not able to transmit the required information to the viewers' client devices. In practice the use of announcements was not possible due to the limitations in the size of payloads current BLE protocols (such as iBeacon) can transmit. In addition, BLE beacons are not well-suited to transmitting large quantities of data and instead typically transmit identifiers for resolution by the receiver [32]. This confirmed the initial findings of Davies et al. [15] for the need of map providers for defining a display personalisation network. As a result, our deployments rely entirely on maps to provide information about displays and their capabilities. Reflecting on the use of maps in our instantiation of Tacita, we note that *current beacon technology is not suited to supporting the architecture proposed by Davies et al. [15]*

```
{
  "id": "24061166-c3ea-45e3-afc7-c027f9e82fdd",
  "meta": {
    "description": "DisplayNetDisplays",
    "start_date": "02/12/2017",
    "expiration_date": "02/01/2018",
    "publication_date": "02/12/2017",
    "map_version": "1.2"
  },
  "domains": [{
    "name": "Lancaster Campus",
    "proxy": "https://example.com/content_request",
    "entries": [{
      "user_region_as_triggerzone": false,
      "regions": {
        "circular_regions": [{
          "lat": "54.01093",
          "long": "-2.78445",
          "radius": "30m"
        }]
      },
      "trigger_zones": {
        "circular_regions": [],
        "proximity_beacons": [{
          "beacon_major": "24",
          "beacon_minor": "6",
          "beacon_type": "iBeacon",
          "beacon_uuid": "d8e40b29-7649-428e-b80c-ba3ed0911fb4"
        }]
      },
      "capabilities": {
        "uuid": {
          "display_id": "display-7",
          "display_name": "CS Foyer Display"
        },
        "display_apps": [{
          "name": "Bus Departures",
          "callback_url": "https://example.com/tacita_callback",
          "description": "Bus Departures description",
          "icon_url": "https://example.com/tsp_bus_logo.png",
          "homepage": "https://example.com",
          "config_url": "https://example.com/config"
        }]
      }
    }]
  }]
}
```


Fig. 3. JSON map description of Display Gateways, Tacita Channels and display and iBeacon identifiers.

in which display and application capabilities are announced to the user as they walk-by. In contrast, map-based solutions provide a significantly more flexible, robust and scalable solution.

4.4 Tacita Channels

Tacita relies on users installing a mobile phone application and subscribing to one or more map providers. The Tacita Mobile Client provides users with a list of available Tacita Channels that can be activated (Figure 4, left). Once the user activates one or more channel(s), Tacita will try to show content from the activated channel each time the user walks by a public display. If the user has activated more than one channel, displays will currently select content from one of the activated channels at random. The Tacita Mobile Client also allows users to configure each available Tacita Channel with their own preferences (Figure 4, middle). The previous system by Davies et al. [15] was limited to simple name-value pairs of configuration parameters. In order to support full flexibility in the design and functionality of configuration pages, however, we designed the Tacita Mobile Client to dynamically load a configuration page from the Web server of the corresponding Tacita Channel. This change was essential to support advanced features such as OAuth2-based authentication mechanisms.

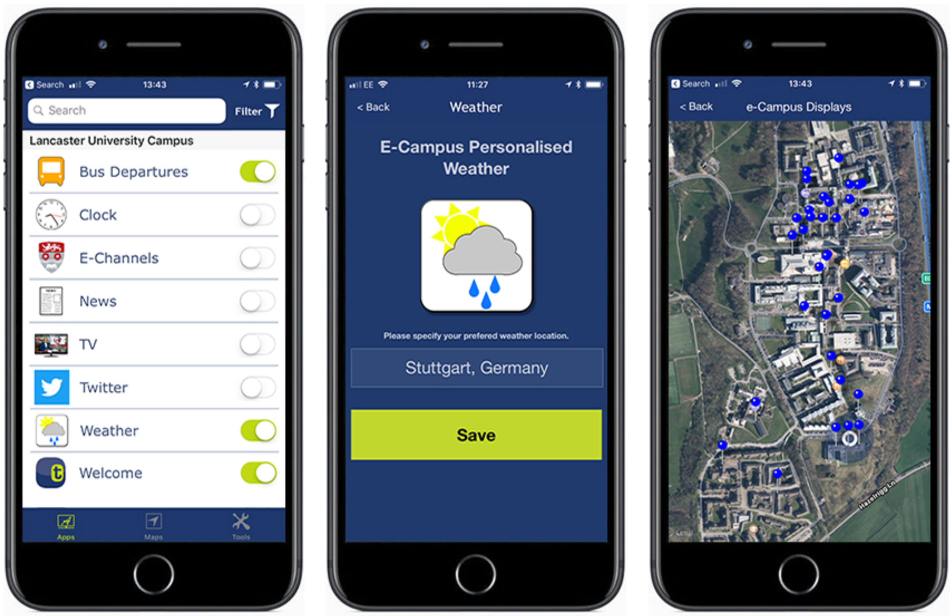


Fig. 4. Screenshot of the Tacita Mobile Client for iOS devices: list of Tacita Channels (left), configuration page for the Weather Channel (middle), and the map of supported displays (right).

In addition, the application detects user entry to/exit from trigger zones, and issues corresponding requests to Tacita Channels. All of the information necessary to populate the lists of Tacita Channels, displays (Figure 4, right) and trigger zones is contained in the map(s) to which the mobile app is subscribed. We created two distinct implementations of the Tacita Mobile Client.

4.4.1 iOS Client. The iOS client provides the full range of Tacita functionality, including map downloads, preference specification and the issuing of display personalisation requests. Unless the user is actively configuring their preferences, the application remains suspended in order to conserve power and only wakes when a user enters or exits a trigger zone. We detect these events using Apple's `CoreLocation` framework which allows up to 20 regions to be monitored in the background by the device so that the application does not need to be running for the events to trigger. Since Tacita maps frequently contain more than 20 trigger zones (where one trigger zone is typically associated with each display) we actively monitor the 19 nearest trigger zones and reserve the remaining trigger zone to monitor significant user movement[3]. When a user first opens the application, we define a 100 meter radius around their current location to track significant movements, and additionally register the nearest 19 display trigger zones. Whenever the `CoreLocation` framework triggers an exit event indicating that the user has moved outside the defined area, the Tacita client de-registers all previously set up trigger zones, and registers a new set of the 19 trigger zones closest to the user's current location. Additionally, the application registers a new significant movement monitoring area with a 100 meter radius around the user's location. The use of the `CoreLocation` framework ensures the energy-efficient tracking of users as the operating system controls the processing time available in relation to the current resources

[3]Significant movement detection is based on iOS significant-change service which relies on WiFi, GSM, accelerometers and other sensors to reduce energy drain.

available and aggregates location monitoring requirements across multiple applications. The iOS client consists of 3, 184 lines of Swift and has been available in the Apple App Store since May 2017.

4.4.2 iLancaster Integration. In common with many universities, Lancaster University offers a mobile application for staff, students and visitors that provides access to a wide range of university services including timetabling, student portals, room bookings, fault reporting and travel information. This application is based on a generic cross-platform framework called campusM that is supplied by Ex Libris and that is commonly used in the university sector. At Lancaster University the *iLancaster* application is very widely adopted, being used by almost all students and many staff on a daily basis. To help lower the barrier of entry for new users at Lancaster University we have created a version of the Tacita Mobile Client that is integrated into *iLancaster*.

The architecture of the *iLancaster* Tacita Mobile Client is significantly different to our iOS build. In particular, beacon detection is carried out by the campusM framework and sent to a University-owned cloud-service. Notifications of mobile clients detecting a beacon are subsequently issued by the cloud-service and forwarded to our system. We created a custom web service that receives these location notifications and subsequently invokes the Tacita Channels on the mobile device's behalf. In addition to handling beacon sightings, our web service also provides a list of available Tacita Channels to users—from which they can set their preferences. As a result, the user interface for the *iLancaster* Tacita Mobile Client is broadly comparable to the iOS native application and the configuration pages for individual Tacita Channels are identical as these are served by the Tacita Channels.

We deployed both the iOS and *iLancaster* versions of the Tacita Mobile Client. However, while we were able to deploy the iOS version prior to the start of the new academic year access to the *iLancaster* platform is tightly controlled and we were required to conduct a phased release of the software to user groups on campus throughout the trial period.

Our experiences of developing mobile applications for Tacita suggest that *the initial approach of using simple name-value pairs to build configuration pages for Tacita Channels is not sufficiently flexible to support a wide range of configuration options.* Moreover, *the overall Tacita architecture appears to be usable with Tacita Mobile Clients with significantly differing architectures.*

5 TACITA CHANNELS

To provide meaningful and relevant content to users of Tacita we have developed a set of Tacita Channels. As a reminder, each Tacita Channel is a personalisable application (or piece of content) that is trusted by both users and screen owners to supply content for public displays in response to requests from users.

5.1 Example Channels

Prior research conducted by Clinch et al. [11] used focus groups and surveys to uncover user attitudes to display personalisation and to determine the types of content users imagine that they would wish to view. In particular, Clinch et al. [11] report a strong preference amongst users for triggering traditional signage content such as news, information, campus maps and clocks – though the authors note that their respondents often wanted such applications personalised to reflect their own preferences. The same work reports little interest amongst users in showing content derived from social media applications, with the exception of Twitter. Drawing on this work, we decided to initially focus on creating exemplar Tacita Channels in four main categories (Table 1): *transport and navigation*, *news and information*, *social networks* and *entertainment*.

Table 1. Tacita Channels for available to the user for subscription and personalisation.

Category	Channel
Transport and Navigation	Bus Departures
News and Information	News World Clock Weather e-Channels
Social Networks	Twitter News Feed
Entertainment	Live TV Pictures
N/A	Welcome

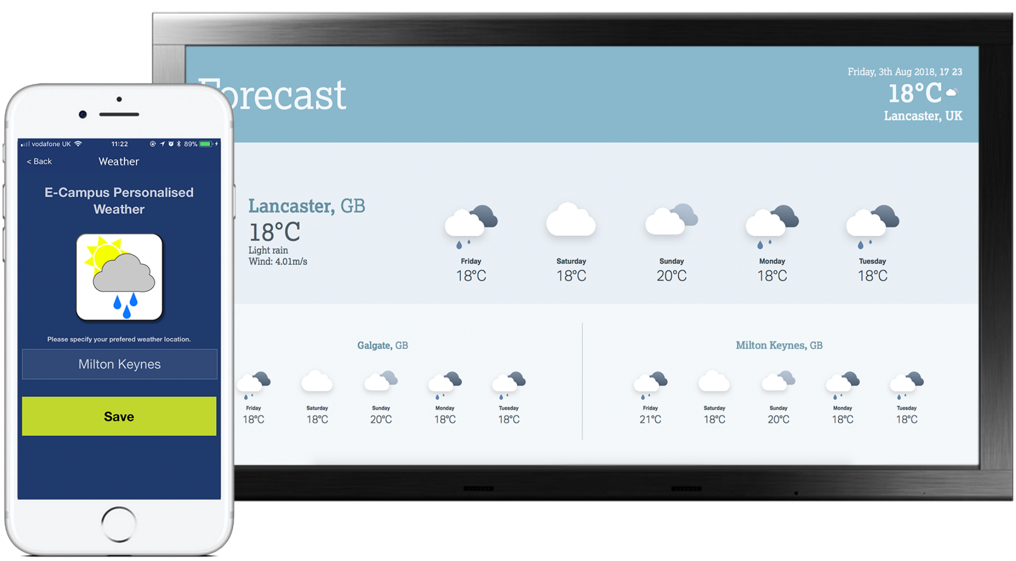


Fig. 5. Screenshots of the Weather Channel configuration page (left) and the visualisation that appears on public displays (right).

The *transport and navigation* category encompasses Channels that enable users to view personalised travel information. Our exemplar Channel provides real-time **Bus Departures** for the user's selected bus stops.

Within the *news and information* category we have created five sample content Channels. The delivery of personalised news and information throughout the signage network, including both news from inside our organisation and news supplied by third-parties is a common use case. Users interested in seeing national and international news can use the **News** Channel to chose from a selection of news sources and categories (e.g. World, UK, Sport, Science etc.) – the display will show a randomly ordered set of news stories from two of the sources chosen by the user. A **World Clock** Channel allows users to select the name of a town/city/country for which are interested in seeing the time. The result on the displays is a set of 3 clocks – one showing the display's local time, one the time in the user's chosen place, and final clock shows time in a capital city chosen at random. The order these are displayed is randomised so it is not immediately obvious to other viewers which is the personalised location – helping to preserve Tacita's original focus on plausible deniability [15]. In a similar vein, we have implemented a **Weather** Channel that allows users to view forecasts associated with their chosen location (Figure 5). Both World Clock and Weather support the aggregation of requests from multiple simultaneous users – for example, the two locations shown in the bottom pane of Figure 5 (the Weather Channel) may be a single user's requested location together with one randomly selected location (as described above) or may be locations requested by two separate users. As per the description above, it is not visually possible to distinguish these two use cases at the display. Our final *news and information* Channel (**e-Channels**) provides access to campus news, allowing users to select from a number of available pools of University content [20]. Each content creator is able to mark their content as Tacita-enabled in which case it will appear in a list of available content for mobile users.

Reflecting prior research that indicated that Twitter might be the *social network* of most interest on pervasive displays, we implemented a **Twitter News Feed** Channel allowing users to show either tweets from their own timeline or, by choosing a specific hashtag, to present public tweets that contain the specified tag. In both cases the display will show the set of tweets (in a similar format to the news app). The Twitter Channel is atypical both in requiring a user account to function and in providing a mechanism whereby a user could cause a display to show inappropriate content (e.g. by requesting tweets to be shown that contain offensive material). We partially mitigate against this by only displaying textual tweets and by screening these tweets using a simple "bad word" filter.

Our final category, *entertainment*, includes two Channels. **Live TV** offers a selection of UK television content for users at Lancaster University to tune into on the displays as they pass by. The **Pictures** Channel allows users to choose from a set of categories such as landscapes or art and shows appropriate images of that category on nearby displays – essentially allowing users to appropriate public displays as picture frames for artwork that reflects their own interests.

Finally, in addition to Channels in the four categories, we also support a **Welcome** Channel that is pre-enabled on each new installation of the Tacita Mobile Client, thus providing a simple way to introduce users to the system. There is no configuration for the Welcome Channel – whenever it is active it causes proximate displays to show a generic Tacita greeting that encourages viewers to turn on and configure other Channels.

5.2 Implementing Tacita Channels

All of our Tacita Channels perform a number of common functions:

(1) They provide a Web-based interface that can be accessed via the Tacita Mobile Client allowing users to submit channel-specific configuration parameters (e.g. location for a personalised weather forecast).
(2) They handle incoming requests from users' mobile devices for content to be shown on a particular display.
(3) They issue requests to the Display Gateway for screen real-estate – typically to enable content to be shown to support walk-by personalisation but potentially to support longitudinal personalisation (in these cases, requests may not correspond to specific trigger zone notifications).
(4) They provide content for displays (typically in the form of a dynamic Web page) if the requests to the screen real-estate have been successful.

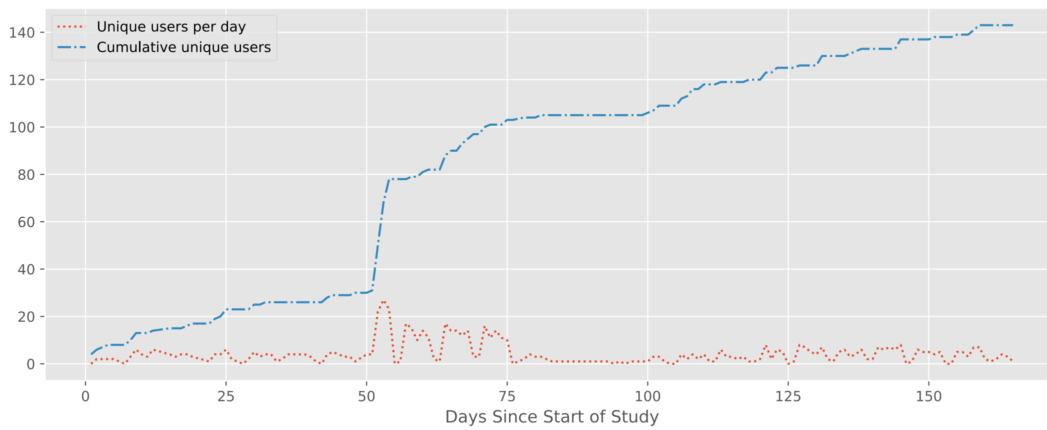


Fig. 6. Tacita users at Lancaster University over the study period of 165 days (the period of rapid growth reflects the period of active recruitment).

There is a high degree of similarity in the basic structure of most Tacita Channels and hence we have created a development framework that can be used to reduce the effort required to create new Channels. This Python framework provides support for creating web content that supports all four functions required by Tacita. In essence, the framework provides facilities for capturing and storing user preferences (using a Web page and SQLite database respectively), responding to user requests to display content and providing the logic necessary to request screen real-estate (by making requests to the Display Gateway), and serving content as appropriate. As a result of the framework, creating a typical Tacita Channel that serves a static web page to users as they pass by displays requires less than 20 lines of Python (the library itself comprises approximately 650 lines). While the framework supports most Web content, the Twitter and TV Channels required additional bespoke coding. In the case of Twitter this was to support user authentication and OAuth2 key exchange with the Twitter API. For the TV Channel, additional code provided access to live multicast streams.

6 METHODOLOGY AND DATASETS

Our evaluation combines quantitative and qualitative analysis. Quantitive data allows analysis of real-world usage patterns (Section 7) and benchmarks system performance (Section 8). Qualitative methods are used to understand individual attitudes to personalisation of an established digital signage network (Section 9). In the following sections we first describe the methods and set-up for the quantitative analysis and then the methodology for qualitative data capture and analysis.

6.1 Quantitative Analysis of Tacita Performance and Usage

Our study is based on quantitative measurements collected from our deployment at Lancaster University. In total, we collected measurements over 165 days (almost 5.5 months, starting in May 2017) and 44 Tacita-enabled displays. This dataset consists of 224, 189 events (including 24, 673 content requests) from a total of 147 unique users (this count considers only users who both installed the Tacita Mobile Client[4] *and* interacted with Tacita at least once over the duration of the study). Since the study took place shortly after Tacita was deployed for the first time, the user base grew over time as new users discover the availability of the application; see Figure 6. We

[4]Either the dedicated iOS client application or users activated the Tacita feature inside inside *iLancaster*.

made efforts to advertise the available Tacita Channels through videos distributed across the public display network – making viewers aware of the new personalisation services.

All components within the Tacita ecosystem were instrumented (Tacita Mobile Client, Tacita Channels, Display Gateways and display nodes), and the following timestamps were captured:

(1) Tacita related beacon sightings on the mobile phone (iOS only),

(2) Request received from the Tacita Mobile Client on the Tacita Channel,

(3) Request received from the Tacita Channel on the Display Gateway,

(4) Display showing the requested content.

In detail, event *(1)* was captured directly on the iOS client application as soon as the iOS background process allocated processing time to Tacita (triggered by an iBeacon sighting). We assume that device timestamps are time synchronised through Apple's time server. The iOS-based Tacita Mobile Client additionally created a random request identifier (UUID version 4) that was included as part of the request body to the Tacita Channel. This request identifier remained part of the request body throughout the remaining chain of APIs, allowing us to capture the flow and latencies of a single request throughout all system components. For events *(2)-(4)* , we logged each request server-side including a timestamp of the event occurrence with the clocks of all the server components being synchronised. To capture the latency between system components, we collate logs from all server components and match them based on request identifier.

In addition to measures based on content requests triggered by beacon sightings, we also capture user interactions with the Tacita Mobile Client. These include each occurrence of users interacting with the Tacita mobile phone application (captured through iTunes Connect Analytics[5]) and accessing configuration pages of individual Tacita Channels. In particular, the usage logs captured by each individual Tacita Channel contain each access to the configuration page and the configuration values chosen together with an anonymous user identifier and a timestamp.

In addition to the field deployment described above we also conducted a series of controlled and laboratory-based experiments that focused on understanding the performance and accuracy of our BLE-based viewer proximity detection.

6.2 Qualitative Analysis of Tacita Usage

Our qualitative studies aimed to develop understanding of patterns of use seen in the quantitative usage data. In particular, we set out to understand perceptions of *value* and *perceived risk*, associated with the capability to personalise the University digital signage deployment, from the perspective of two core stakeholders: *display viewers* (and thus potential or actual users), and *content creators/-managers*. Whilst attempts have been made to capture these attitudes before, our interviews took place several months after the deployment of Tacita rather than relying on abstract scenarios or prototype artefacts [11]. In addition to informing discussions about value and risk, our engagement with display viewers was intended to capture experience of both using the Tacita Mobile Client to configure personalisation preferences and of viewing personalised content on public displays (including, for example, any potential usability concerns). Together, this consideration of values, risk and experience draws on the rich literature on technology adoption models which typically consider perceived value, usefulness, and perceived risks as key factors influencing adoption of new technologies, such as display personalisation.

6.2.1 Engagement with Display Viewers. The Tacita mobile application is intended for download and use by display viewers, allowing them to select from a range of available Tacita Channels

[5]iTunes Connect Analytics is a service provided by Apple to all iOS developers. Data is only captured from users who have actively opted in to collecting app usage analytics on their device.

and share their content requests with nearby displays. However, to reach this point, each user must first install their preferred mobile application and then proceed through a configuration process in which they select their preferred Tacita Channels and enter any additional configuration parameters on a per-Channel basis (Figure 4, left and centre). Subsequent interactions with the application require significantly less (or even zero) engagement.

In this study, we therefore focus on new users' initial experiences of Tacita. We explore the degree to which display viewers find value in the Tacita, exploring which (if any) Tacita Channels would be likely to prompt them to adopt the application for continued use. We conduct set of interviews using the Tacita (iOS[6]) mobile application as an interactive prop and probe in which we observe participants as they go through the install and configuration process, discuss perceived value and risk, ask them to highlight any usability concerns.

We do not conduct any targeted research with a large population of established Tacita users. Whilst this would have some additional value in understanding the motivating factors in ongoing use, a combination of factors make recruiting from this population infeasible. Firstly, a combination of Tacita's measures to ensure privacy and anonymisation policies that formed part of our research ethics application meant that we were unable to contact Tacita users directly. Secondly, overall prevalence of Tacita use remained low (approx. 0.8% of the population throughout the deployment period reported in this work) meaning that simply sampling the population was unlikely to be effective at recruiting established users.

Sample: Interviews were conducted in accordance with the University's ethical guidance and the study protocol was granted institutional ethics approval. We recruited a small pool of members of the target population (Lancaster University campus occupants) that did not presently use any of the Tacita mobile applications. Seven participants[7] were recruited in-person using opportunity sampling at three busy but representative *e-Campus* display locations – each selected display was located in the foyer of a multi-use building, with 2-3 participants recruited at each of the three sites. Demographic information was not collected but all participants were current undergraduate or postgraduate students at Lancaster University. Participation was incentivised with a small chocolate bar or piece of fruit.

Method: Each interview lasted approximately fifteen minutes and consisted of:

- an initial study briefing and consent process,
- a verbal description, provided by the researcher, of the Tacita application,
- a demo of the application, and invitation/guidance to (install and) configure the application and observe the result of configuration on the nearby display, and
- a short interview (10 questions) with participant responses captured using in-situ note-taking.

Materials: Our participants had no prior experience of Tacita but were invited to install and use the iOS application on their own phone for the duration of the interview: three participants chose to do this. A further three were willing but unable due to device/OS compatibility; those unwilling or unable to install the application on their personal device were invited to use a researcher's device for the duration of the study.

6.2.2 e-Campus Stakeholder Interviews. In addition to capturing attitudes of display viewers, we also sought to understand the impact of providing display personalisation on those who produce and manage content. In particular, we were keen to again understand perceived costs and values:

[6]Our qualitative study focused on the iOS implementation since this was the most readily used implementation at Lancaster University.

[7]One further participant volunteered for the study but their data was excluded when they later revealed that they had already installed and configured the application on their phone.

whilst Tacita provides a novel mechanism to distribute targeted content to students and staff, it also brings additional burden on this stakeholder group (requiring more items of content to be produced, and more nuanced decisions about who should be shown what). We therefore conducted our final set of interviews with *e-Campus* stakeholders with responsibility for creating and controlling content across the display deployment. These stakeholders already engage with *e-Campus* on a day-to-day basis, creating and distributing University press content and key messages (e.g. news internal to Lancaster University, information about events targeting students, staff and visitors), and making decisions around the university-wide distribution of content from third parties such as student societies and other departments.

Sample: We recruited a sample of four *e-Campus* stakeholders who were invited to participate based on their roles as *content creators*. Participation was not incentivised.

7 ANALYSIS OF USAGE PATTERNS

We begin our analysis by investigating usage patterns of the in-the-wild deployment at Lancaster University with the aim of characterising how personalised displays are used outside controlled settings. In addition, we investigate the spatial distribution of personalisation requests across campus. As the source of data, we consider the usage and application logs captured through the users' mobile devices as well as request logs and configuration parameters recorded on Tacita Channels. Our analysis contrasts with prior research on public display personalisation that has predominately focused on investigating technical aspects such as the use of Bluetooth identifiers to provide personalised content [14] and providing novel forms of content and applications [28] but has lacked the long-term deployments that enable research into usage patterns.

7.1 Channel Selection

Display personalisation enables users to express a preference for the type of content they wish to see on pervasive displays. Understanding these preferences provides insights that can help (i) shape the development of future personalisation applications (e.g. by identifying applications and content that appeals to a user base and target the development of future applications towards that direction) and (ii) influence display owner's choice of content to show on non-personalised screens (e.g. by including content that was often requested from Tacita users and may therefore be of interest to non-Tacita viewers in other locations).

We study content requests for the nine example Channels available in our deployments; see Section 5.1 and Table 1. Focusing on content requests means that we only consider users that have requested a Channel to be shown on the display at least once and thus we filter out those users who just explore configuration possibilities of a Channel without actually using it.

Table 2 shows the percentage of total Tacita users who have used each Channel (excluding the Welcome App) at least once. Note that users can have multiple active Channels and hence the table does not capture absolute preferences but rather provides an indication of the relative levels of interest in different content types. On average our users selected a small number of the available Tacita Channels – mean 2.95 of the 9 available Channels per user (SD. 1.67). Personalised travel information (Bus) is clearly the most popular Channel, followed by the Weather Channel. Our sole example of a social media Channel (Twitter) is one of the least popular forms of content[8], lending credence to the findings reported by Clinch et al. [11] in which viewers expressed little interest in

[8]A single anomalous day with very large numbers of Twitter requests can be seen in Figure 8. Comparison with Figure 7 shows that very few unique users actually made requests during this time. Further examination of the request logs confirms that two individuals repeatedly requested the twitter account related to a single student social organisation.

Table 2. Details of Channel adoption showing the percentage of total users who issued at least one content request to the Tacita Channel and the availability of the Tacita Channel during the study period. The *Availability* column reflects the fact that Channels were deployed over time, and thus not every Channel could be used for the full duration of the deployment period. Note that 100% usage for the Welcome Channel reflects that fact that this Channel is pre-enabled on each new installation of the Tacita Mobile Client rather than any user choice.

Category	**Tacita Channel**	**Availability (%)**	**Users (%)**
N/A	Welcome	100%	100%
Transport and Navigation	Bus Departures	100%	64%
News and Information	Weather	100%	40%
News and Information	World Clock	100%	35%
News and Information	News	100%	24%
News and Information	E-Channels	100%	24%
Entertainment	Live TV	100%	22%
Social Networks	Twitter News Feed	100%	8%
Entertainment	Pictures	86%	7%

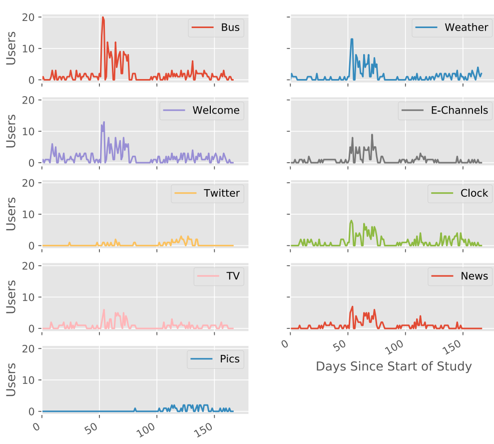


Fig. 7. Total number of unique users per day per Channel. Spikes around day 55 coincide with a period of active user recruitment.

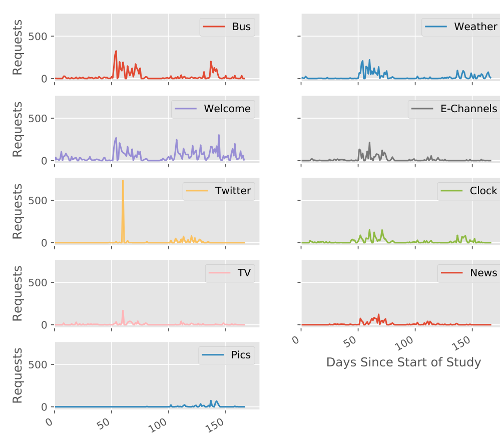


Fig. 8. Total number of requests per day per Channel. Spikes around day 55 coincide with a period of active user recruitment.

being able to show such content on public displays. While most Tacita Channels were available throughout the study period, we introduced Pictures part-way through the trial (Table 2).

Figure 7 shows the number of unique users on campus per day for each Channel. The graphs clearly reflect a period of intense advertising and recruitment (62 days in) and the timetabled nature of campus life with requests dipping during the holiday period (days 87-114). Similar patterns can be observed when considering the total number of requests per day across all users, as shown in Figure 8.

Most content requests were issued automatically by the Tacita Mobile Client as a result of beacon sightings (i.e. walk-by personalisation rather than explicit personalisation). Only 1.4% of content requests (356) were triggered manually, i.e. users specifically opened the Tacita Mobile Client to manually request a piece of content. These requests originate from a total of 65 users (44.2%) who manually requested content at least once – primarily on the first day that they used the Channel. Only 11 users manually requested content on more than one study day (collectively issuing a total of 140 manual requests). These statistics show that only a minority of users manually adjusted the content while standing in proximity of a display, supporting a view that pervasive displays should be designed with minimal interaction requirements to ensure continued usage.

Dealing with competing requests, i.e. how to handle simultaneous content requests from multiple users, is a potential challenge for any large-scale deployment of pervasive displays. Whilst the scale of our deployment was not enormous, it represents by far the largest research deployment of displays, and hence provides us with an opportunity to examine the significance of this problem. Based on the data captured, it would seem that the number of competing requests from different users were negligible, with only 0.03 mean competing requests (median: 0.00; SD: 0.04) per day per display location, defined as requests from at least two users that arrived for any Tacita Channel for the same display within a time window of 30 seconds.

As discussed in Section 5.1, the Channels available in our deployment were chosen as representative examples motivated by earlier stakeholder interviews and findings reported in prior research literature. Overall we can observe that requests mainly focus on informative content rather than social media or entertainment – and therefore differ from commonly used applications in mobile phone contexts. We therefore recommend that display installations seeking to support personalisation initially focus on developing and deploying information channels. Personalised travel information was particularly popular on our campus but obviously this may vary based on the individual situation of the display installation. Our long-term usage data seems to suggest *that there is a strong correlation between Channels users report as potentially interesting and those they use in actuality* – easing the process of selecting which channels to prioritise.

7.2 Spatial Patterns of Requests and Display Dwell Times

We next consider the spatial patterns of content requests together with the duration of users' proximity (dwell times) at different displays, with the aim of understanding how display location and participant mobility influences content selection. To explore these patterns, we leverage mobility traces based on trigger zone entry and exit events indicating when viewers arrive and leave the vicinity of a display; see Section 6.1.

Figure 9 visualises the spatial distribution of content requests. Each circle corresponds to an individual display with the colour of the circle reflecting the total number of requests for the display – green indicating low numbers of requests, red indicating high numbers of requests. Considering the requests across all Channels we can observe that viewing patterns reflect dynamics of university life – display locations with the highest numbers of requests include locations that are both physically and philosophically central to University campus life: the library and communal study area. Locations with a lower number of requests include the University's conference centre, departmental buildings and locations near the borders of the campus. While not surprising, this indicates that beacons attached to display deployments can indeed capture and reflect the everyday dynamics of people using them.

We separately considered the spatial distribution of content requests for four example Channels one from each category (Figure 11): Bus Timetables (the most popular Channel, Figure 11b), Live TV (average popularity, Figure 11b), News (average popularity, Figure 11c), and Twitter (the least popular Channel, Figure 11d). We observed small differences in the distribution of content requests for each of the Channels including a tendency for Twitter to be used in areas such as the communal study area, library and lecture theatres that are frequented more by students than staff.

We also compute the mean *dwell time* of viewers at each display location, providing us further insights regarding the behaviour of viewers and the characteristics of individual displays locations.

Fig. 9. Numbers of requests of Tacita Channels per display location (green: low number of requests of approx. 15; red: high number of requests of approx. 1800) across all Channels.

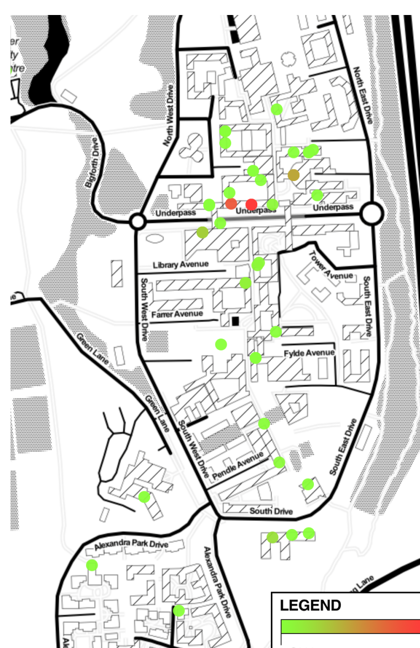
Fig. 10. Dwell times of viewers in front of displays (green: low dwell times of approx. 50*s*; red: high dwell times of approx. 360*s*). The dwell times have been normalised based on the displays with the highest and lowest dwell times respectively.

The resulting dwell times are shown in Figure 10 and clearly reflect the nature of the physical environment in which the displays are deployed – display locations with high dwell times include the library, communal study area, and a subset of student bars, reflecting the larger amounts of time students and viewers typically spend in these areas. Other locations such as building foyers have relatively low dwell times, supporting the suggestion that viewers tend to only walk by such displays. *The learned knowledge from analytics about typical dwell time can be used as an important factor in the design and delivery of content.* Short dwell times suggest that viewers are typically walking by and therefore are required to notice and comprehend content in only a very short period of time. Further, the prompt delivery of content becomes crucial to catch the viewer while they are still in the vicinity of the display. For locations with higher dwell times, the prompt delivery of content becomes less important. These locations are also able to host more complex content as viewers will have more time to comprehend the material. Overall our results show that insights into viewer dwell time can be extracted with reasonable accuracy merely by using beacon sightings.

(a) Bus Departures

(b) Live TV

(c) News

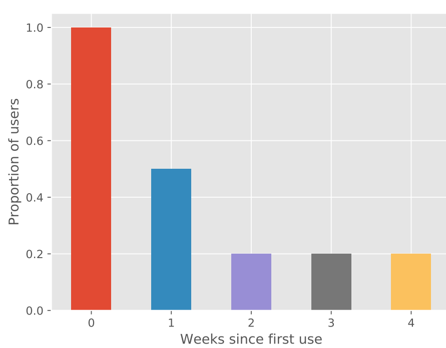


(d) Twitter

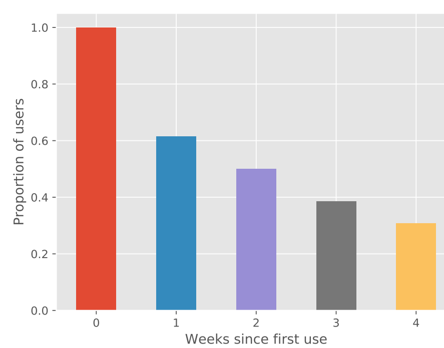
Fig. 11. Numbers of requests of individual Tacita Channels per display location (green: low number of requests; pink: high number of requests).

7.3 Personalisation Opportunities and Duration of Usage

Experience with traditional mobile applications suggest that one of the major challenges is to maintain a high (active) user base. Tacita, of course, features a unique set of characteristics in that the system continues to function without requiring the user to actively engage with the mobile application. Once Tacita has been activated and configured on a mobile device, walking by a display is sufficient to cause an implicit interaction. This behaviour continues until a user decides to deactivate or deinstall the mobile client application. Whilst we are unable to capture such events due to restrictions on the data available from the App Store (i.e. application uninstalls are not typically reported), we can utilise the durations in which we see continuous user requests as an indication as to whether users are still willing to keep Tacita on their mobile device. In order to provide further insights into the implicit and explicit interactions, we consider two datasets: content requests based on user proximity to displays and access to configuration pages of Tacita Channels.



(a) Winter term

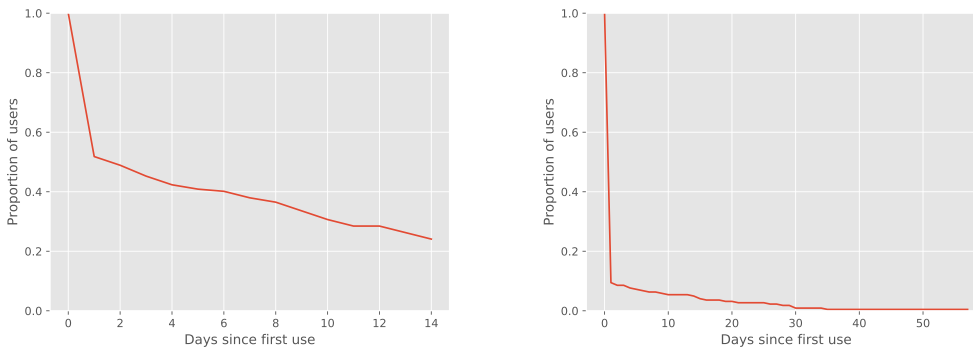


(b) Spring term

Fig. 12. Proportions of users making requests over a period of five weeks.

We use content requests as an indicator of *engagement* with Tacita Mobile Client. Note that content requests are only issued when users are within the proximity of a Tacita-enabled display and hence the absence of a content-request within a given time-window can not be solely attributed to abandonment/failure of the Tacita Mobile Client application. We account for this by factoring in assumptions regarding viewer behaviour. In particular, we assume that the vast majority of our viewers study or work at the University and thus are likely to have timetabled activities that will dictate that they are present on campus at least once a week during term time – thus if we do not see a single content request from a viewer within any given week we assume that their Tacita Mobile Client application is no longer operational. Figures 12a and 12b show how content requests decline over time under these assumptions.

Figure 13a provides further detail, showing how the proportion of users making requests falls over a period of 14 days since they installed Tacita Mobile Client (again restricting the analysis to term time). The graph shows a sharp drop after one day – suggesting that a significant number of people try the application and then either uninstall the application or change their system configurations to prevent it from making content requests. However, we also observe that after seven days approx. 37% of the initial user base continue issuing personalisation requests to Tacita Channels and after twenty-one days this figure only drops to 22% of the initial user base (Figure 13a).



(a) Personalisation requests issued by Tacita users walking by displays.

(b) Users accessing configuration pages of Tacita Channels.

Fig. 13. Usages of Tacita over time. Plots show the proportion of users making one or more requests (a) or configuration changes (b) over time.

We acknowledge that the number of active users in our study declines – emphasising some of the challenges that come with long-term and real-world deployments and highlighting the need for such studies. Based on our experience, a number of factors influence whether content requests are issued. On users' mobile devices, the Tacita Mobile Client relies on a number of factors: users are required to give the Tacita Mobile Client access to their location at all times – and specifically while the application is in the background; both Bluetooth and WiFi must be active to support better location-tracking and detection of iBeacons; at least one Tacita Channel must be activated; and, users are required to have mobile data enabled at the time at which an iBeacon is detected. If any of these requirements are not met the Tacita Mobile Client is unable to issue content requests to a Tacita Channel. Given these demands we believe that Tacita still manages to maintain a very respectable number of *active* users.

We observed that it became difficult to maintain the same user base over a longer break period. In particular, the winter vacation period (i.e. between terms 1 and 2; a property very specific to campus universities) marked an almost complete change in the set of observed user identifiers (97% of identifiers observed in term 1 were not subsequently seen in term 2). This could indicate a significant level of churn amongst users or that a number of users reinstalled or changed phones during this period which would result in then being allocated new user identifiers (due to our anonymisation policies, we do not allocate users with persistent identifiers).

In order to describe engagement of users with mobile applications over longer periods of times, researchers previously utilised 'retention' as a standardised metric defined by the number of days between the first and last use of the mobile application [51]. In the context of Tacita, using 'retention' as a metrics is not suitable due to the nature of the application in which requests and 'engagement' can happen without the requirement to the user to explicitly interact with the application. Certain interactions with the Tacita Mobile Client, however, do require explicit user intervention and can be used as a basis to get some insight about retention figures with the Tacita Mobile Client itself – not with the system overall. In particular, opening the application in order to configure individual Tacita Channels (e.g. to provide personalisation parameters to individual channels such as preferred locations for weather forecasts). Using such access logs to configuration pages from Tacita Channels can be used as a source to measure retention with the Tacita Mobile Client itself

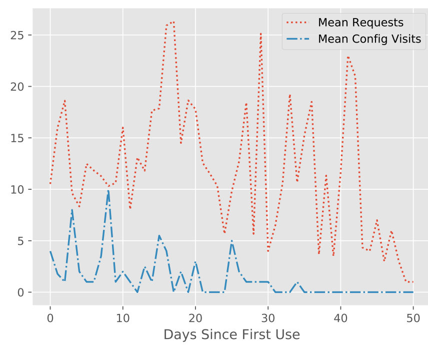


Fig. 14. Mean number of requests per user per day, and mean number of configuration visits per user per day, based on the number of days elapsed since the user's first day of use.

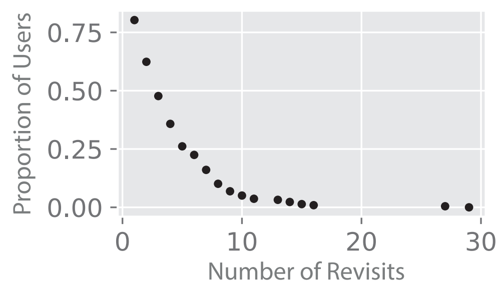
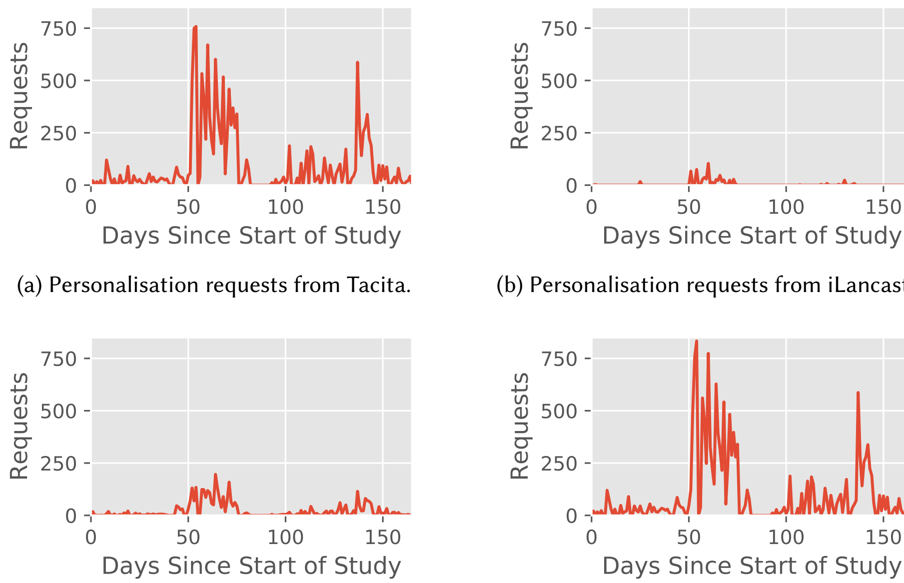


Fig. 15. Proportions of users revisiting configuration pages of Tacita Channels during the study period.

– however, *we note that this does not indicate the overall retention and engagement with the Tacita system overall.* The interactions captured with the Tacita Mobile Client itself appear to be rather low (Figure 13b). This is also reflected in a small number of application launches captured through on-mobile analytics (mean 2.1 sessions per day; SD: 4.76). The low number of mean users per session per day in comparison to the number of installations suggests that the app is primarily used for the initial set-up phase. Similar insights were gained by computing the cumulative distribution function for the proportion of users revisiting the configuration pages of individual Tacita Channels. Figure 15 reveals that over 75% of users revisit the configuration page only once, and over 50% a second time.

As described in Section 4.4, Tacita was deployed using two separate mobile phone applications: a stand-alone application for iOS devices, and an integration into *iLancaster*. Due to the slow roll-out of the Tacita integration into *iLancaster*, the majority of users originate from our native iOS-based Tacita Mobile Client, as shown in Figure 16. In particular after showing advertisements across the University campus and internal student and staff news portals combined with active recruiting, the popularity of the native application significantly increased and the user base doubled within just two days. This effect can also be observed in Figure 6 showing the number of new users over time.

In summary, our usage analysis based on recurring personalisation requests (Figure 13a) together with the mean number of requests per day (Figure 14) provide some indication that display personalisation systems are indeed used over longer periods of time – yet by lower proportions of users than initially expected. Furthermore, our data showed evidence that users are very reluctant to revisit the Tacita Mobile Client in order to reconfigure their personalisation preferences in individual Tacita Channels. Instead, users appear to activate and configure preferred Tacita Channels and leave the system activated without any further interaction or reconfiguration. Such usage patterns are contrary to our initial expectations and provide a number of challenges such as making users aware of new Tacita Channels and content within individual Tacita Channels. As part of this finding we believe that providing a personalisation system that works 'out of the box' without the requirement for user configuration, and perhaps even automatically reconfigures itself over time would ultimately improve the utility for users.



(a) Personalisation requests from Tacita.

(b) Personalisation requests from iLancaster.

(c) Failed personalisation requests.

(d) Total number of requests.

Fig. 16. Numbers of personalisation requests.

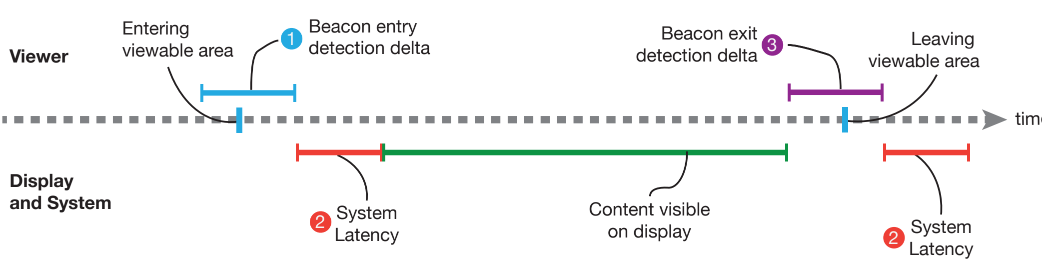


Fig. 17. Overview of the content delivery process in pervasive display systems together with critical events affecting the proximity detection performance. User's entry (1) and exit detection deltas (3) depend on the underlying proximity detection technology, whereas system latency (2) depends on network and system performance.

8 PERFORMANCE ANALYSIS

8.1 Overview

In this section we analyse the overall system performance of Tacita and, in particular, its ability to support the most challenging use case of display personalisation: walk-by personalisation.

The overall goal of display personalisation systems is to maximise the content *exposure* and *accuracy* (as defined in [15]), i.e. to deliver personalised content to the display at exactly the same time as the user enters the display's viewable area and remove the content as soon as the viewer leaves the viewable area. Figure 17 illustrates the three key sources of delay or inaccuracy that impact on content exposure and accuracy measures:

(1) Beacon Entry Detection Delta represents the time delta between the viewer entering the viewable area of a display (and the adjacent BLE beacon) and the point at which the background location tracking detects the viewer's proximity to the display's beacon. This delta will be positive if the proximity was detected *after* the viewer has entered the viewable area of the display and negative if the proximity was detected *before* the viewer entered the viewable area of the display.

(2) System Latency describes the delays incurred in processing the request for display personalisation. This includes the API call from the viewer's mobile device to the Tacita Channel provider, and subsequent calls from the Tacita Channel to the Display Gateway, and the display node as well as the time taken to begin rendering the appropriate content.

(3) Beacon Exit Detection Delta represents the time delta between the viewer leaving the viewable area of a display (and the adjacent BLE beacon) and the point at which the background location tracking detects that the viewer is no longer in proximity of the display's beacon. The delta for leaving a beacon range will be negative if the detection takes place *before* the viewer leaves the area and positive if the detection takes place *after* the viewer leaves the area.

In the following sections we systematically analyse each of these sources of delay or inaccuracy.

8.2 BLE Beacon Performance for Display Personalisation

8.2.1 Experimental Setup. To establish the on-device delay in detecting proximity to iBeacons we conducted two experiments: one in controlled laboratory conditions and the other using our real-world testbed. For both experiments we utilised an iPhone 6 as the mobile device and a custom mobile application that captured timing data for the following two distinct beacon detection mechanisms:

Monitoring: Core Location Framework The recommended mechanism to implement BLE beacon detection on iOS devices is Apple's Core Location framework [5]. The framework supports the detection of beacons for both standby and active modes of the device, i.e. specifically supporting the tracking of beacons whilst the application is in the background. The Core Location Framework does not support the specification of any configuration parameters, e.g. to influence the detection frequencies. In the subsequent sections we will refer to this technique as *monitoring*.

Ranging: Core Bluetooth Framework The Core Bluetooth framework [4] allows developers to range for proximate Bluetooth devices – including BLE beacons. This method requires both the device and the application using this technique to be active and in the foreground. In contrast to *monitoring*, using the Core Bluetooth Framework allows the specification of detection frequencies and therefore provides the ability to develop custom entry and detection algorithms. In the subsequent sections we will refer to this technique as *ranging*.

The use of *monitoring* (the recommended approach to beacon detection and technique implemented in the Tacita Mobile Client) and *ranging* (fine-grained control over detection frequencies) allowed us to evaluate the beacon detection approach utilised in our real-world deployment (monitoring) and compare it with the theoretical best-case performance (ranging). Use of *ranging* on iOS requires the device to be active – therefore making this approach infeasible for an in-the-wild deployment in which the detection of viewer proximity to displays is achieved whilst the device is not in active use.

8.2.2 Performance of On-Device Beacon Proximity Detection under Controlled Conditions. To evaluate the on-device beacon detection performance in laboratory settings we used a controllable

Table 3. Median, mean and standard deviation for enter region (beacon detected) and exit region (beacon lost) events (seconds). Note that the ranging functionality in iOS is only available with the phone in *active* state.

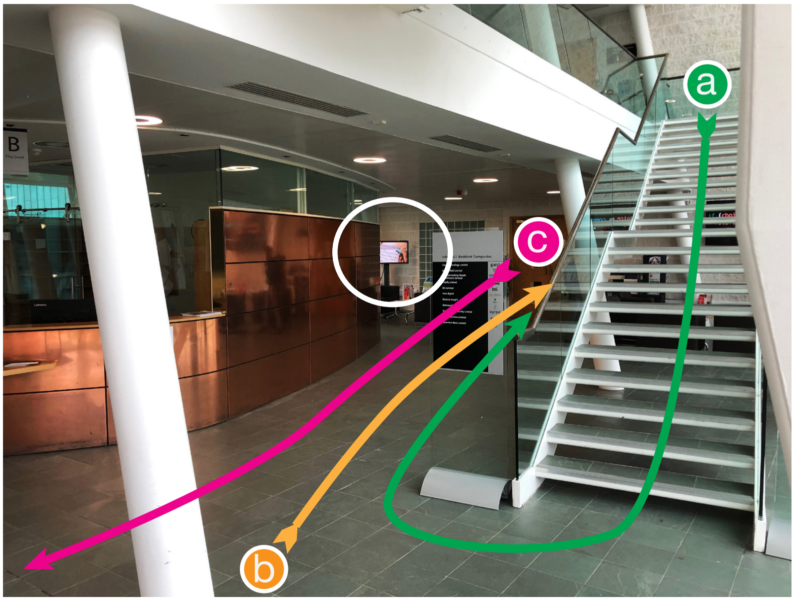
		Enter Region			**Exit Region**		
Condition	Phone State	Median	Mean	SD	Median	Mean	SD
Monitoring	standby	2.00	3.11	2.48	29.25	28.73	2.01
Monitoring	active	0.57	0.88	0.84	30.05	29.78	0.86
Ranging	active	0.73	0.71	0.30	10.37	10.33	0.27

iBeacon that we could turn on and off in order to simulate viewers entering and leaving the transmission range of a beacon. We performed 10 repetitions of activating and deactivating beacon transmission for both monitoring and ranging. We captured the latency between activating the beacon transmission and the point at which the beacon was detected by the mobile device. We also evaluated the performance of leaving the proximity of a beacon by capturing the time delay between deactivating the beacon transmission and the point at which the beacon was detected as "lost" by the mobile device. For *monitoring*, we compare two states of the mobile device: active (i.e. with the screen turned on and the phone unlocked) and inactive (i.e. with the screen turned off and the mobile device on standby). For the ranging mode, we only use the mobile device in active mode as active ranging in the background is not supported.

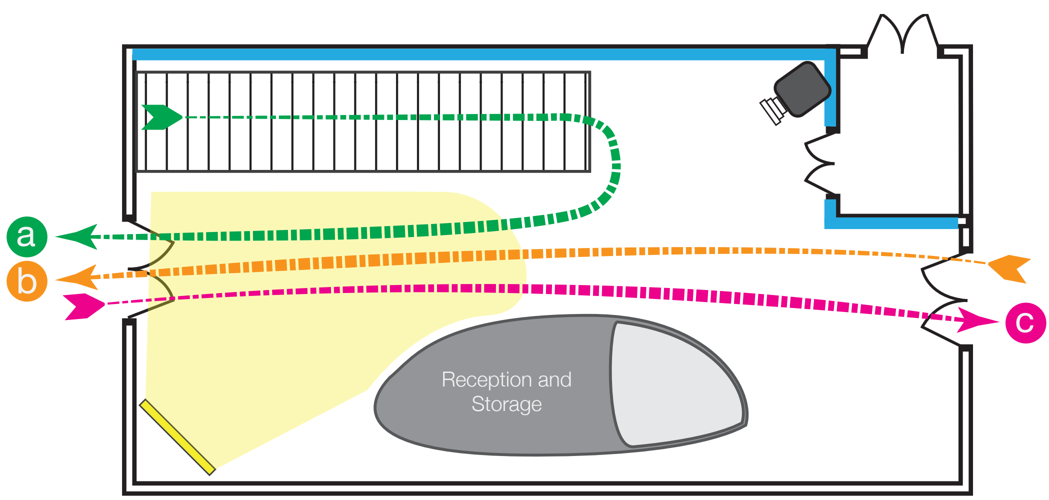
We found that the entry detection (i.e. simulating the case in which the viewer enters the proximity to a display) performs well across both monitoring and ranging with the device in active mode. However, the standard deviation for the monitoring technique is slightly higher suggesting the potential impact of other background processing tasks running on the operating system leading to ranging as the most reliable and stable beacon detection technique. With the device in standby mode, the standard deviation for detecting the user's entry into the monitored area is noticeably higher with a median of approximately 2 seconds. Given an average walking speed of $\approx$ 1.4 m/s (5 km/hour), detection based on either ranging or monitoring allows the viewer to move approximately 1-5 meters before their proximity to the display is detected depending on whether the mobile device is in standby or active modes. Based on a typical range for BLE beacons (and Bluetooth transmission in general) of approximately ten meters, the latency would still allow the system to react to the viewers presence in the viewable area fast enough to change the content in time – providing that the beacons have been configured with an appropriate signal strength.

Performance of the a monitoring device atexit detection was significantly poorer than entry detection, with a median delay of 29.25 seconds (SD: 2.01) and 30.05 seconds (SD: 0.86) with the device in standby and active mode respectively. We believe that this is a result of iOS treating background location tracking for leaving areas with a lower priority, or applying larger thresholds before an exit event has been sent to the client application. Using ranging as a technique, we were able to achieve a significantly better and more stable performance with a median of 10.37 seconds (SD: 0.27) – still significantly poorer than for entry detection. We note therefore that if the display infrastructure relies on timely exit detection to free up display real-estate and remove personalised content, both monitoring and ranging may be unsuitable.

8.2.3 Performance of On-Device Beacon Proximity Detection under Real-World Conditions. We designed a follow-up experiment in a realistic setting in order to investigate the influence of the physical environment on the detection accuracy of beacons on mobile devices. We identified a representative deployment within the e-Campus display network and defined three walking paths that are typical for many of our displays (Figure 18):



(a) Picture of the experimentation area annotated with the three routes and the display location in the back.



(b) Layout (not to scale). The display can be seen from positions within the yellow shaded area.

Fig. 18. Floor plan of the controlled walk-by experiments to capture beacon entry and exit detection latencies.

(A) the viewer approaches the display from another floor of the building, travelling through an open staircase – introducing the difficulty of detecting the viewer as they move between floors,

(B) the viewer walks towards the display from a nearby location on the same floor of the building with no significant interfering physical structures – representing the most common form of walk-by personalisation in our display deployment,

Table 4. Median, Mean, and standard deviation for entry detection from entering and leaving the viewable area of the display respectively.

		Enter Region			Exit Region		
Route	**Condition**	**M [s]**	**Mdn [s]**	**SD [s]**	**M [s]**	**Mdn [s]**	**SD [s]**
(A)	Ranging	3.19	2.73	3.66	10.22	10.50	1.85
(A)	Monitoring	3.66	−1.01	15.72	26.32	31.65	10.68
(B)	Ranging	5.58	5.48	3.7	10.18	10.30	1.59
(B)	Monitoring	5.10	4.89	3.24	31.37	43.89	39.38
(C)	Ranging	1.65	0.90	1.95	12.07	11.56	2.96
(C)	Monitoring	−1.23	−0.20	7.21	33.14	36.35	11.42

(C) the viewer walks towards the display from a nearby location on the same floor of the building but separated from the display by a concrete wall.

We conducted a set of walk-by experiments and captured the following events using a combination of in-person observations and data from our custom mobile application (introduced in Section 8.2.1):

(1) the viewer entering the viewable area of the display (visualised in yellow in Figure 18b), i.e. the first opportunity the display can be seen ,
(2) the mobile device detecting the proximate beacon (entry event), i.e. the earliest time at which the system is able to react to the viewer,
(3) the viewer leaving the viewable area of the display, and
(4) the mobile device detecting that the viewer has left the proximity to a beacon (exit event).

For each of the three routes, we set the device in active mode and conducted 10 repetitions each for both ranging and monitoring.

Our data indicate that beacon detection in these more realistic settings is highly variable, and results depend heavily on the walking path and detection technique used (Table 4). Similarly to the results observed in the controlled lab-based experiments, ranging yielded significantly lower standard deviation for both entry and exit detection across all routes. By comparison, monitoring led to more variable, but earlier (in some cases, preemptive) entry detection with means of −1.01, 4.89 and −0.20 seconds for routes A, B and C respectively. The significant difference between the results for routes A and C as compared to route B can be explained by the fact that in routes A and C the viewer enters the radio range of the beacon before entering the viewable area of the display (e.g. by approaching the display from behind). This is a reported issue with using proximity for display personalisation [14]; our results provide further evidence of the need for personalisation systems to support absolute location rather than relying on proximity detection. The higher standard deviation for monitoring is likely to be caused by variability in the scheduling of the beacon detection process by iOS.

In contrast to entry detection, we observe a significant improvement when using ranging instead of monitoring for exit detections in the wild. In addition to a lower latency for detecting viewers exiting the viewable area of a display, we can also observe a lower standard deviation, yielding a better consistency in the detection times. The mean detection time using monitoring as a technique was 31.65 (SD: 10.63), 43.89 (SD: 39.38) and 36.35 seconds (SD: 11.42) for routes A, B and C respectively. In contrast, we were able to capture mean detection time using ranging at 10.50 (SD: 1.85), 10.30 (SD: 1.59) and 11.56 seconds (SD: 2.96) for the three respective routes. Fast (but

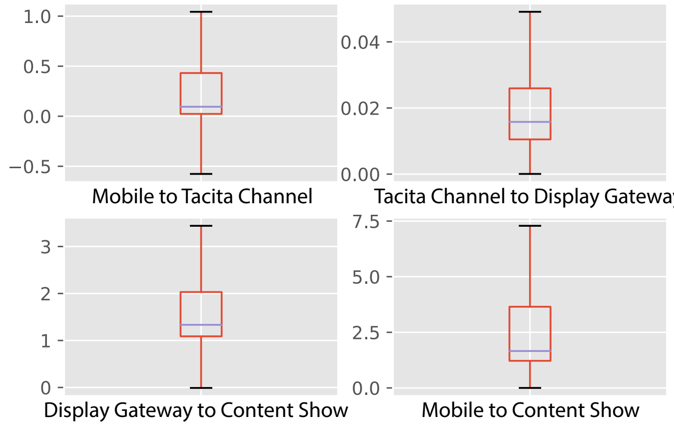


Fig. 19. Latency in seconds for each component of the Tacita system, and the total from the mobile request to the point at which the content is displayed (bottom right). Box plots show median, first and third quartiles, with whiskers stretching to 1.5 times the interquartile range.

positive) and reliable exit detection is important for freeing up display real estate once the viewer has left the viewable area.

Entry and exit detection latencies are highly dependent on (1) the spatial layout of the area in which the display and BLE beacon have been placed, (2) potential background tasks and radio processing on the viewer's mobile device, and (3) the technology used to detect viewer proximity. For example, the mean detection for route B using monitoring as a detection technique (4.89 seconds) allows the viewer to walk $\approx$ 6.5 meters before successfully being detected in the proximity of the display. Based on our results and experiences, it is therefore important to note that a wide range of factors contribute to inaccuracies and delays of viewer proximity detection using BLE technology – and that many of these factors lie outside our control. Improving detection times to support walk-by personalisation can be achieved by tuning the power and placement of the BLE beacon. However, this is still prone to significant variations due to the wide variety of mobile devices used and variations in the context of use (e.g. the number of people present in the area). BLE is also affected by interference which suggests avoiding placing the beacons very close to WiFi access points or other transmitters. Significantly, whilst BLE beacons can be configured and placed in a way to detect viewers in time to support *walk-by personalisation*, the technology does not appear to be reliable enough to support consistent viewer tracking (e.g. to capture the duration in which viewers dwell in the viewable area of a display) with a very low detection error.

8.3 Tacita System Performance

In the previous section we considered the on-device performance of detecting beacons in proximity to the user's mobile device. However, as shown in Figure 17, entry and exit detection deltas are only two factors impacting the overall content exposure and accuracy of Tacita. The third factor is the system latency introduced by the architecture of Tacita from processing display personalisation requests through all system components including Tacita Channels, Display Gateways and display nodes. For the results presented in this section we consider the data captured during the long-term in-the-wild trial described in Section 6. Analysis provided in this section omits data from E-Channels; this Tacita Channel differs significantly in its implementation (in part due to its integration with an existing system [20]) making it impossible to generate the required measurement data.

Table 5. Median, mean and standard deviation (in seconds) for each latency between each Tacita component. Timings are measured from initial beacon detection at the Tacita Mobile Client to content shown at the Public Display.

System Components	Median [s]	Mean [s]	SD [s]
Tacita Mobile Client to Tacita Channel	0.09	2.15	16.52
Tacita Channel to Display Gateway	0.02	0.19	5.82
Display Gateway to Content Show	1.33	3.16	7.19
Tacita Mobile Client to Content Show	1.66	4.80	11.75

8.3.1 End-to-End Latency. The final row in Table 5 presents the total end-to-end latency of Tacita from the point at which the user's proximity is detected to the point at which content is shown on a display. The figures are averaged from data collected from all users throughout the trial period. The median end-to-end latency is 1.66 seconds (mean: 4.8, SD: 11.75). Given the previously-described average walking speed of 1.4 meters per second this latency translates to just over two meters, indicating that the transmission range of beacons would need to be adjusted accordingly in order to account for this system-related delay.

8.3.2 Component-Specific Latency. Table 5 (and Figure 19) presents a breakdown of the latencies measured for individual Tacita system components. The latency between detecting an iBeacon at the mobile device and receiving the request at the Tacita Channel appears highly variable (median: 0.09 seconds; mean: 2.15; SD: 16.52). Latency for detecting and reporting the proximity of beacons is highly dependent on the data connectivity of the user's mobile device and the speed with which the device detects a proximate beacon. During testing, we observed the highest latencies in situations where the user transitions from outdoor to indoor environments (i.e. displays located in building entrances and foyers). The forwarding of requests from the Display Gateway to content shown on a Public Display is the largest source of latency (median: 1.33; mean: 3.16; SD: 7.19). This is mainly due to overhead associated with the Yarely scheduler, which invokes a new content scheduling and selection process upon receiving requests from the Display Gateway in order to enable dynamic content change. This latency could be slightly reduced by improving the performance of the scheduler.

8.4 Additional Considerations

As part of our evaluation we also measured the *reliability* of Tacita by calculating the number of content requests that did not result in content being shown on a display. Requests in Tacita typically fail due to one of three reasons: (1) the requested content is not available, (2) the display is already showing higher priority content or, (3) the display receives multiple, conflicting, personalisation requests. Figure 16c shows the total number of failed requests per day. Compared to the total number of requests, the number of failed requests is relatively low. This suggests that Tacita and its subcomponents are reasonably robust in their handling of personalisation requests. However, we note that with an increase of users the number of failed requests caused by conflicting requests is also likely to increase.

9 STAKEHOLDER AND USER ATTITUDES ANALYSIS

9.1 Engagement with Display Viewers

In order to explore potential users' attitudes to values, risk and user experience of Tacita we conducted a series of interviews. Our seven interview participants all owned and used a smartphone:

four were iOS users (of which one used an older version of iOS and could not install the Tacita Mobile Client) and three were Android users.

Initial responses to the system were positive, with six participants indicating that they would be willing to install the application if they had a compatible device (three installed the application during the interview, the remaining three were not running a compatible version of iOS on their own device). The remaining participant (an Android user) indicated they would not want to use the system, citing concerns about the potential for ambient content to act as an interruption, commenting that they had *"already disabled push notifications on my phone... knowing that the displays are there... would result in me looking, hence interrupting me – even if I just pass by" [P2].*

In line with our Tacita Channel usage data, when asked about Tacita Channels that they thought they would be likely to use, over half of our participants (4) listed Bus Departures as their most likely candidate; for 2 of these users, Bus Departures was their sole motivation for using Tacita. Other Tacita Channels mentioned by participants included the Clock (4 participants indicated that they would be likely to use this), Weather (3 potential users), News (3 users), TV (2) and e-Channels (1). This list of Channels corresponds well with those reported by Clinch et al. [11] in their 2014 study, with the notable exception of the Bus Departures Channel – this content was not envisaged by subjects in this earlier study but has been demonstrated to be the most popular Channel in our deployment.

Six participants had suggestions for new Channels including personal study timetables, local (university) events, and availability of meeting rooms/group study spaces (these three were the only Channel suggestions to be made by two or more independent participants). Other suggestions were: campus map, personal calendars, round-robin emails, Instagram, and a Channel that allowed users to broadcast their own content to others.

Both participant questionnaires and their actual usage during the experimentation session suggest that in many cases some minimal personalisation of the Channel is desired by users. For example, in all cases, participants suggested that they would use the clock or weather to view locally-relevant data (in line with findings by Clinch et al. [11]).

The Channels cited as being least useful were often those for which the participants considered that they would be more likely to *"look up [the information]... on my phone" [P3].* For one participant [P2] this was all content, and for a further two this was all information bar the bus timetabling. Two participants initially identified that they would chose not to use the Twitter Channel (for privacy reasons), two the default Tacita Welcome Channel, and one the TV Channel (due to the content being shown for too shorter period to be useful). However, once the interviewer raised the issue of privacy concerns, a further two participants expressed reluctance to use the Twitter Channel (i.e. four participants in total), and one of these suggested that social media in general may be problematic. Other Channels generally raised few privacy concerns, with just one participant [P7] highlighting that TV or News may also betray personal preferences, and one raising concerns about targeted advertisements moving from the web to public displays [P2].

Concerning the Tacita Mobile Client itself, two users wondered about the potential impact on their device's battery life *"Yeah... as long as it does not drain my battery, I would consider [using Tacita beyond the context of the interview]" [P7].* Two users requested manual control of the times at which Channels could appear (the Tacita Mobile Client currently supports the manual request of Tacita Channels but does not support fine-grained control over the time frames during which Tacita Channels should appear). This is potentially significant as it suggests a temporal element to personalisation control that we had not previously considered and that is not apparent in prior literature.

Some minor alterations were also suggested to improve the user interface (e.g. increasing button size). Finally, three users raised concerns about the display behaviour in situations where multiple users are proximate to the screen simultaneously, with two wondering what the resulting behaviour would be, and a third noting that *"I'm not sure I would... be certain it's me who triggered [the Channel]" [P4].*

Overall, following completion of the demo and experimentation with Tacita, most users remained positive about the system despite privacy concerns and an observed trade-off between the value of seeing ambient content (*"I like the system's potential to serve as an easy reminder... getting information you are not necessarily looking for" [P4]*) and the potentially unnerving appearance of personalised content in a public space (*"using the system could be a bit uncanny from time to time if personalised content appears while I walk past the display." [P7]*).

9.1.1 e-Campus Stakeholder Interviews. Our four interviews with other stakeholders targeted those with responsibility for creating and controlling much of the content for *e-Campus* displays and initially focussed on exploring their knowledge and attitudes to Tacita. Three of the content creators were able to provide a good overview of Tacita's functions while the fourth professed to no knowledge of the system – for this content creator we provided a brief overview of Tacita's key features. In common with our end-users, the content creators were all positive about the concept of the Tacita system. It is important to note that while our content creators routinely created content that could be viewed by users of Tacita this was in the form of general channels of content for the signage system – they they did not need to explicitly consider Tacita users during this process. While it would be possible to create specific channels or content for Tacita users our content creators had not chosen to do so. None of the content creators reported having received any negative comments regarding Tacita, and none had any concerns regarding expansion of the system.

Interestingly, our content creator experiences were all related to their professional roles as content creators and controllers – none of the content creators were end-users of the Tacita Mobile Client (despite all being members of University staff and therefore potential users). When asked about this, reasons cited included the sense of already being overloaded with information (*"I naturally resist quite a lot of information" [C1]*), lack of awareness [C3] and a lack of space (data storage) for new applications on their phone [C4]. More generally there was a sense that since they spent every day dealing with the flow of campus information, they had little need to avail themselves of extra sources: *"Because I've been at Lancaster for a long time, and because I work in a team where it's our job to know what's going on, I would already know a lot of the stuff" [C4].*

Regarding the future use of Tacita, there was considerable enthusiasm for its use as a means of targeting specific segments of the campus community (*"Need to do better with comms for students on campus. Tailoring messages to them – it could help with that" [C1].* This led to an interesting discussion on whether Tacita could automatically determine information about a user (e.g. their student status). While such automatic profiling and subsequent personalisation might be possible, it is not currently supported in the version of Tacita and appears at odds with our desire to enable users to remain in control of display personalisation. A second suggestion from stakeholders was the use of Tacita to provide information in viewers' native languages. While this is not critical for most information – there is an expectation that students are proficient in English – it could be of immense value for emergency announcements that are shown on the screens. We intend to explore this potential use in detail as the benefits could be considerable.

10 SUMMARY AND CONCLUSIONS

In this paper we reported on our experiences of creating and deploying a system to support personalisation of pervasive displays by mobile users, the first such real-world deployment to take place at scale (in terms of number of displays, duration of deployment, *and* number of different items of personalisable content/applications). Through the process of actually conducting a real-world deployment, we identified the need for an additional component not described in prior architectural explorations of pervasive display personalisation. Building on the findings presented in Section 4 we make eight key observations that may be of value to others looking to deploy systems with a similar purpose:

(1) Architectural approaches that rely on trusted applications communicating directly with displays are unlikely to be compatible with the security practices and heterogeneity of real-world deployments. In addition, the modification of individual deployed displays is undesirable, and potentially impossible, in established settings. Introducing a new Display Gateway component to act as the network entry point provides a practical compromise between the desire for a clean and simple architectural model and the constraints of real-world deployments.
(2) Modular and open approaches to public display architectures and software have been described in the prior literature [8, 10, 17, 37, 53, 54]. Such approaches can add complexity to the initial development, but for the first time, we provide a concrete illustration of the benefit of such approaches when adding new functionality. Use of the Yarely [10, 37] open signage software enabled easy addition of new components to accommodate changes in context provision and scheduling preferences.
(3) Current beacon technology limits the use of privacy approaches that reverse the traditional beaconing model such that displays broadcast their presence and capabilities to mobile users rather than the other way round. Previously-proposed *optimisations* that involve the use of maps to describe display capabilities become *mandatory* when using current commercially-available beacon technologies.
(4) The early display personalisation prototypes described in Davies et al. [15] suggested the use of key-value pairs to describe configurable (personalisable) aspects of display content. As content evolves, this over-simplistic model becomes unviable. Allowing Channel providers to create their own user-facing configuration endpoint, to be embedded into the Tacita application, allowed us to overcome the inherent inflexibility associated with key-value pairs.
(5) The growth of pervasive, out-of-home digital displays has led to the creation of a wide variety of underlying conceptual architectures, hardware and software systems. Likewise, technology for mobile users is highly heterogeneous. New innovations that allow mobile users to leverage their personal technologies to engage with pervasive displays will likely only succeed if they can achieve compatibility with the plethora of display and mobile technologies. Our implementation demonstrates that the overall Tacita architecture is compatible with Tacita Mobile Clients with significantly differing architectures.
(6) Positioning display personalisation as additional functionality for existing applications is both possible and desirable. Initially, we pushed for uptake of our native implementation of our Tacita Mobile Client as it offered a number of benefits for our study including providing full control over display proximity detection and extensive logging to support developing insights into system latencies and reliability figures (e.g. tracking of personalisation requests from the point at which the beacon was detected on the mobile device). However, articulating a value proposition for users that motivated them to install the new application was challenging – convincing users to use Tacita via *iLancaster*, an application that already provides a high number of benefits to students, was much easier. This experience suggests that instead of providing dedicated applications to enable display personalisation, such functionality should instead be integrated in larger-scale applications (e.g. those that already provide news and information to users) to gain a larger active user base.

(7) Challenges exist in supporting evolving user preferences: users appear unlikely to return to the Tacita Mobile Client in order to (re-) configure Tacita Channels. The relatively small number of users who change their preferences matches trends seen in other domains (e.g. the limited number of users who update security preferences on a regular basis). However, this raises a number of challenges, in particular how to engage users with new Tacita Channels and new features within existing channels. In reality the fact that Tacita is able to present content to users via public displays may have to be capitalised on to provide an effective channel for disseminating information to users.
(8) An unexpected benefit from deploying Tacita was the fact that the insights gained from analysing user content requests could be used by display owners and content creators to shape their offering on other (non-Tacita enabled) displays. For example, in a network such as ours where many users configure Tacita to display travel information display owners may wish to increase the amount of travel information shown as part of their standard carousel of content – benefiting even users who did not subscribe to Tacita. Furthermore, the insights into dwell times at displays can be used to inform the selection of appropriate content durations or even the location of new displays. More generally, this illustrates that benefits can be accrued with even partial rollouts of appropriately instrumented personalisation systems.

In addition to the observations that emerged through the process of building and deploying Tacita, this paper also examines usage of display personalisation when made available in an established deployment for an extended period. Whilst short term studies can provide valuable opportunities to work systematically through a number of variants (to assess, for example, user uptake under a variety of conditions), we have instead focused on creating a fully operational service that can be used to provide a concrete example of the use of mobile technology to personalise pervasive displays. Our experiences enable us to answer questions that are most commonly asked when considering the use of mobile technology for display personalisation, namely:

Will anybody actually use a display personalisation system? Our usage data analysis presented in Section 7.3 attempts to quantify the degree to which users engage with Tacita. Overall, our data analysis shows that we were able to recruit a large number of users (over 147 throughout the study period) of which approx. 37% continue to appear as active users issuing content requests after seven days and approx. 22% after three weeks of from the first time of use. We note some challenges in tracking usage data whilst also maintaining anonymity – our mobile client deliberately generates a new user identifier with every reinstall of the Tacita application. Our results clearly show that a portion of users are prepared to engage with a system such as Tacita and that they continue to do so for extended periods of time. Throughout the trial period our installed user base continued to grow. Considering the number of users who *explicitly* engage with Tacita (e.g. by requesting content or accessing configuration pages of Tacita Channels), we observe that it remains a challenge to motivate users to access the Tacita Mobile Client and users generally appear to be less likely to reconfigure Tacita Channels after the initial configuration period – an insight that needs to be considered in the design of potential future systems. While the number of explicit interactions each user has with the Tacita Mobile Client may be low, our observations show that users continue to leave the application operating in the background despite the obvious energy cost associated with running a location-based application in this way. We do see a high turnover of users during the vacation periods; this may be partially explained by changes in devices and application reinstalls, but we also note that vacations would be extended periods during which Tacita failed to deliver any value (away from the campus a users' personalisation requests would have no impact on their environment). During these periods users may well have turned Tacita functionality off in order to conserve power or network resources, and then subsequently failed to re-enable the functionality on their return to campus. This data suggests that whilst users are indeed willing to initially experiment with a novel application and appear to be configure it, it is indeed challenging to maintain an active user base over longer periods of time – despite the fact that manual intervention and active use of Tacita is not required to retrieve personalised content on displays after the initial set-up period.

What content will users want to see? The Channels we provided were motivated by findings emerging from preliminary stakeholder discussions and prior research [11, 15]. Channel usage data (Section 7.1) showed a strong preference for the Bus Departures Channel (achieving almost double the number of users of any other Channel); Bus Departures also received the most positive feedback during our qualitative interviews. Bus travel is an important feature of campus life, as noted in Section 3 a majority of students and staff commute (typically by bus). Our Channel usage data also validates prior observations [11] that personalised social media content is unlikely to be a good choice for public displays. Again our interview data confirms this view, with only one suggestion for social media content (Instagram) emerging from our prompt for potential new Channels. This contrasts with mobile apps where social media is typically considered one of the most popular application categories. We attribute this lack of interest to two main factors (i) growing awareness of privacy concerns and (ii) ease of access to private content. In the first case, we note that recent trends towards increased privacy awareness, particularly relating to social media platforms [22, 42]. In the second, we observe that even if users are willing to share their private content, to do so requires additional configuration steps (e.g. sharing of API keys, username/password authentication) thus increasing the burden of time and expertise, potentially beyond the point at which the user is willing to engage. Thus, social media applications for public displays typically only provide access to public content (e.g. [14]), while users can easily access both public and private content on their mobile device.

It remains unclear what the *killer application* for personalised pervasive displays might be. While in our deployment transport content was the most popular, we would not wish to argue that travel apps themselves are the "killer application". Rather, we would argue that in the specific context of our deployment (an out-of-town university campus) Bus Departures are important to viewers and hence a popular personalisation choice. This suggests that personalisation preferences are unlikely to be universally applicable – users may be interested in Bus Departures in one location but in local news in another, suggesting a need to explore the use of both personal preferences *and* localised values when designing and deploying personalised content. In line with prior literature, we suggest that this localisation should include demographics and cultural factors influencing content preferences [46]. Further, whilst in our setting users reported that it was a single Channel (Bus Departures) that led them to want to use Tacita, and on average our users selected a small number of the available Tacita Channels, it is entirely possible that in other settings it would be the *cumulative value* of lots of smaller applications that prompt users to value personalised pervasive displays. In both cases, there is benefit in encouraging higher levels of innovation in display application development, as seen in initiatives for the creation of display application stores [12].

What happens if multiple people try and personalise the same display? Handling conflicting requests is a clear area of concern for any system that actuates based on individual input. For public displays, multiplexing approaches (time, space and integrated [3]) allow screen real-estate to be divided across multiple content items and is a problem addressed by the scheduling components that form an inherent part of most signage software. Our use of the Yarely software [10, 37] allowed easy modification to ensure that personalised content was prioritised over other items and that, in the case of conflicting requests, no single user was able to dominate the screens with their own personalised content. Further, the use of this open signage and scheduling software would facilitate further refinement in future, supporting a range of scheduling policies such as prioritising content that is the subject of multiple requests from different viewers, prioritising users who have most recently entered the space, or enforcing specific time-limits in the presence of multiple requests. In addition, through our exemplar Weather Channel we have demonstrated that individual Tacita Channels can themselves be implemented to address the case in which multiple requests are made for the same content, but with different configuration options. How each Tacita Channel resolves this will vary but in this case a simple aggregation allowed multiple users' content to be shown simultaneously. The preference for information-focused content (rather than, for example, entertainment in the form of videos) that we observed in our deployment suggests that this type of content aggregation may be feasible in many cases.

Finally, we note that while conflict is an obvious potential issue, our observations over a period of 165 days suggest that with the current level of uptake such conflicts are rare (mean of 0.03 competing requests per day per display location). Obviously as the uptake increases so conflicts will become more commonplace but there is a significant degree of commonality seen in the preferences expressed by users which also suggests that in many cases conflict-resolution will be unnecessary.

Will display owners allow personalised content to be shown on their screens? Whilst in the context of *e-Campus* the entire display deployment is maintained and 'owned' by a common organisation and personalised content is provided from the same organisation, individuals in charge of the spaces in which displays are deployed (e.g. department administrators for displays located in departmental buildings, college managers for displays located in common areas of student accommodation, and the University communications team for public-facing outdoor displays) have full autonomy over the types of content that appear on these displays. Based on this, we are able to provide some limited insights into the willingness from a display controller perspective to allow personalised content potentially outside of their control. Our previous research [11] suggested that the majority of display owners and managers would be open to personalisation of screens under their control. Despite this, we still approached each of the display owners and managers for *e-Campus* screens to informally discuss the system and to seek consent to deploy Tacita on 'their' screens. As shown in Figure 2, not all screens were Tacita-enabled following this discussion, but the vast majority of display owners did consent to personalised, user-triggered content appearing on their display. Further, during discussions that explained the Tacita system and the additional functionality it would provide, some display owners demonstrated a significant shift from an initially negative perspective (*I'm losing control of my screen*) to being keen supporters of the system – primarily, motivated by the potential to create their own Tacita Channels. Throughout the deployment, display owners and managers were additionally provided with a user interface that allowed them to disable Tacita on their displays (either permanently or temporarily). This facility was embedded into the main display and content control interface [20] and was therefore readily accessible and usable by all. Our observations indicate that after 165 days, all displays that originally allowed Tacita requests continue to do so, suggesting that the system met owner/manager expectations and that they did not perceived the user-triggered, personalised content to detract from their displays.

Furthermore, content creators expressed significant interest in utilising the system to distribute content tailored to specific student, visitor and staff groups. For example, the use of Tacita to show content in the students' native languages in emergency situations was expressed as a plausible and important use case to make student communication even more effective. Under normal conditions, Tacita was described as a valuable system that would allow the communications team to distinguish between, for example, visitors, staff and students and help increase the value of displays by delivering more relevant content to the passers-by. Based on these discussions we believe Tacita has the potential to become part of an integrated content dissemination system in which content creators can schedule content by selecting specific demographics or target groups – without the need to actually select a specific communication medium or group of displays.

How well does the system work from a technical perspective? Our work focussed on assessing the technical feasibility of Tacita (and in particular, the use of BLE beacons to support walk-by personalisation) both in the context of *controlled walk-by experiments* and as part of a *long-term and in-the-wild deployment.*

Our controlled experiments showed current commercial technologies to be capable of predictably determining when users *enter* the vicinity of a display but are prone to significant delays in detecting when a user *leaves* the viewable area of a display. This finding leads to the conclusion that using BLE technology is technically feasible to support the delivery of personalised content in a timely manner for users entering the viewable area of a display but its use inherently limits the extent to which content exposure can be restricted to the time a user is present in the viewable area of a display.

Considering our in-the-wild deployment, we were able to capture a unique set of performance data providing first-of-a-kind insights into the feasibility of a display personalisation system using BLE beacons under real-world conditions over an extended period of time. Our data shows if users' mobile devices successfully detect and report a nearby BLE beacon (i.e. a display location), the subsequent chain of requests feature a sufficiently low latency (median end-to-end latency of 1.66 seconds) that walk-by personalisation can be supported despite the succession of requests required across multiple system components. We observed a limited number of failed requests (i.e. display sightings reported by users that did not lead to a change in content on the corresponding display) compared to the total number of requests as reported in Section 7. However, this observation also reveals the largest challenge of the system: it relies entirely on reliably functioning user mobile devices – in light of the heterogeneous landscape of mobile devices a clear challenge. In our experience, failed beacon detection is mainly a result of a lack of data connectivity at the time of detection, misconfigured mobile devices (e.g. deactivated Bluetooth) and user-chosen privacy settings that prevent background processing or location tracking.

Trends in pervasive computing including mobile sensing and the IoT are creating increasing expectations for environments that adapt with their users in order to improve productivity, comfort, wellbeing and social cohesion. Envisioning the future usage of these personalised spaces is a key input into design and development, but poses considerable challenge in a present where they are not yet commonplace. We believe that the observations and insights presented in this paper will be of value to any researchers or developers considering the creation of smart environments that respond to the presence of mobile users, and in particular to those focused on supporting personalisation of ambient displays.

We fully recognise that there are limitations with the work presented. Firstly, despite our detailed analytics our desire to protect viewers' privacy (given that this is a live service) limit the extent to which we are able to track individual users. For instance, every new install of the Tacita Mobile Client appears as a new user as we were not able to introduce tracking identifiers (e.g. based on device and hardware) that would allow us to recognise the same user after a reinstall. Secondly, there is the obvious question as to whether the results from a single deployment generalise. To help mitigate this we have tried to report on both lab-based studies (e.g. the suitability of BLE for walk-by personalisation) and our field trial. While it is not possible to claim generality of our field-trial results we do believe that the results of our lab studies (and indeed our architectural work) generalise to many different smart-environments. Thirdly, our viewer interviews only cover potential users of the system rather than those with actual experience of the system and their comments should be read in this light. Finally, we note that we have not reported on the use of Tacita to support personalised advertising. Give the popularity of public displays as an advertising medium this is clearly an area of potential future work. In our current trial we avoided exploring adverts because our University chooses not show adverts on its public displays (as a matter of policy) and we wished to respect that policy. The underlying Tacita technology could, of course be used to support such a study.

Considering future work more generally in the domain of ambient display personalisation, we highlight four key areas of importance. **Firstly**, we observe that like similar systems to date, Tacita relies on pre-defined user preferences – users are required to define configuration preferences for each new Channel that they enable. However, a future possibility would be to pursue personalisation techniques that *learn* about user interests based on users' physical and behavioural responses. However, such a system would require more invasive monitoring – this could take place in the context of the users' mobile device (e.g. configuration changes with the Tacita Channel itself, interactions with other mobile applications, web search histories), or within the physical world (e.g. thermal sensing [1], walking trajectories and gait [30], purchase activity [9]). Given our previous observations regarding an increase in privacy-consciousness, such monitoring would potentially result in lower take-up due to its more intrusive nature. Approaches to resolving this privacy/personalisation trade-off would be a critical part of any future self-learning personalised display system. **Secondly**, our experiences with Tacita led us to conclude that local values may be an important factor in the success of personalisable content for public displays. The development of localised content for pervasive displays (e.g. [35]), also referred to as 'situated' content [28, 29], has been an important area of research. However, such projects typically do not additionally attempt to incorporate personal preferences. We suggest that creating tailored content to displays may well incorporate aspects of both personalisation *and* localisation, and future work should explore the intersection of these two approaches. **Thirdly**, our approach (and other prior work) has tackled personalised content selection from the perspective of ensuring a user sees a specific item of content on one or more displays *at a single moment*. In many contexts, the priority may be less about ensuring a content item appears in one place at one time, and more about simply ensuring that the specified user sees the content a given number of times, or for a given duration. Future work may therefore target the design and development of a system that supports the broadcasting of content for specific target groups through a heterogeneous set of devices and modalities. Such a system may encompass, in addition to pervasive, public displays, potentially the private displays with which a user engages on a daily basis (e.g. the user's personal devices). Realising this vision will require new innovations in display and device analytics, content scheduling, context awareness and in privacy preservation. In particular, we see the development of a 'scheduling for the individual' approach as a natural continuation of research that builds on top of existing sensing and analytics technology and ultimately introduces novel means to actuate both private and public displays. **Finally**, given the current focus on walk-by and active personalisation, there is an obvious need for further exploration of the development of systems that specifically target longitudinal personalisation. Current approaches centre on demographic data that can be extracted from visual sensors (e.g. based on height or body shape) and new approaches are needed in order to allow for the explicit targeting of cohorts or segments of the population who may not be distinguishable based on visible characteristics alone. Whilst several of our Channels provide simple measures for handling multiple co-present users, this is a very distinct case for developing schedulers and content items that are intended to change the appearance and utility of displays based on ever-changing user demographics.

The research reported in this paper represents the first deployment of display personalisation at scale, with detailed quantitative analysis for a period of 165 days during which time we supported 24, 673 requests from over 147 users across 44 displays. This comprehensive usage dataset, combined with benchmarking and qualitative interviews allows a broad set of perspectives on viability and usage of future pervasive display personalisation systems. Based on our results, we infer key avenues for future work in the community. In our own research we will build upon the Tacita system and our experiences, by developing a comprehensive signage ecosystem that provides a feedback loop that both *enables* realisation of a 'scheduling for the individual' approach, and allows for *measurement* of the real-world outcomes associated with that scheduling. Such an ecosystem would be a complete transformation of current display systems, tackling the display blindness effects associated with low viewer expectations by providing highly-relevant content. At the same time, it would maintain the priorities held by other core stakeholders, by providing viewing guarantees and, for the first time, allowing those stakeholders to establish the impact of their content on viewer behaviour.

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