Computational Framework to Support Development of Applications Running on Multiple Co-located Devices

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ABSTRACT

We designed a framework to generalize the development of applications with UI elements distributed across co-located devices. The framework is comprised of diverse components in order to deal with the complexity of such a task, including: authentication and authorization services; a broker to sync information across multiple application instances; background services that gather the capabilities of the devices; an indoor positioning system to determine when devices are close to each other; and a library which helps integrating Web applications with the broker, determining which components to show based on UI requirements and device capabilities, and custom elements to manage the distribution of the UI components and the multiple UI application states. Collaboration is supported by sharing UI states with other users.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Ubiquitous and mobile computing**; • **Computer systems organization** → **Distributed architectures**; • **Software and its engineering** → **Software libraries and repositories**; **Development frameworks and environments**.

KEYWORDS

multi-device applications, cross-device interaction, context-awareness, application framework, proxemics, indoor positioning, UX, HCI

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1 INTRODUCTION

People use an increasingly large number of computing devices in their daily lives [15]. However, applications are usually confined to run on a single device at any given time. At best, they are capable of synchronizing certain types of data, and such synchronization often needs to be explicitly turned on [5, 8, 33].

Therefore, there are missed opportunities to build integrated experiences that run across multiple devices. We believe that it is important and beneficial to take advantage of the devices around us by combining them and integrating their resources. It should be possible to leverage the strengths of some devices in certain scenarios, while minimizing the weaknesses of other devices in some situations.

This realization motivated us to develop the tools needed to build applications that have their user interface (UI) seamlessly distributed across multiple co-located devices. In order to fulfill our vision, we designed a framework that generalizes the development of this type of applications and that allows third-party developers to take advantage of the increasing pervasiveness of digital devices.

The initial version of the framework laid the foundation needed to build cross-device application experiences [31]. Later, we focused on the issue of automatically distributing UI components among co-located devices by matching the description of the capabilities of each of the co-located devices and the requirements of each of the application's components [32].

The current version allows users to switch between automatic and manual distribution of the application's UI elements by device. Moreover, while the framework initially kept the current per user and application's UI state synchronized across the application instances running on multiple devices, the framework has since been extended to allow storing multiple UI states per user and application. Furthermore, these UI states can be shared to enable collaboration between multiple users.

These additions were accompanied by the development of reusable components that can be easily integrated into applications. This should allow developers to quickly give users direct control over

the distribution of UI components, the management of multiple UI states, and to enable collaboration by sharing those states.

In the remaining of this paper, we introduce the research areas that support our work (section 2). We then present a technical summary of our framework (section 3). We finish by presenting conclusions and ideas for future work (section 4).

2 RELATED WORK

The framework concept came from previous research on system specific efforts that combined mobile devices with situated displays [25, 30]. We also realized that people started to spontaneously use multiple screens at the same time, e.g., by using mobile devices while watching TV to access trivia and engage with other viewers [9, 20, 21]. There are already interesting works related to second screen applications that provide an enhanced viewing experience [3, 4]. Moreover, based on device shipment trends and developer interest, a multi-device application ecosystem has been previously identified as the next way forward [35]. Users should be able to seamlessly move between co-located devices, performing tasks across them, such as continuing playing the same film on another device, or displaying the playback controls on one device and the media output on another one.

Liquid Software is an approach in which applications and data flow seamlessly across devices, allowing users to continuously switch from one device to the next without having to worry about how to transfer applications, settings or associated data [13]. Responsive Web design partially addresses the issue of running software fluidly on different screen sizes and input modalities, but we still have challenges, such as code mobility, state synchronization, UI adaptation and shared data access [19]. *Liquid.js* is a framework that tackles some of them to enable multi-device applications, which operate on a shared decentralized state using Web-based technologies [7]. *XDBrowser* is another example which segments Web pages and distributes the fragments across devices [22]. Meanwhile, *Vistribute* provides a data analysis framework that adapts to a multitude of devices based on information about the views and the data they visualize [14].

There is also research that is focused on the design space of the multi-device applications. For instance, *McKit* contains scenarios, hint cards, and a framework for understanding the required trade-offs in realistic contexts of use [23], while the *4C framework* identifies four principles for multi-device interaction design: communality, collaboration, continuity, and complementarity [34]. Paternò and Santoro present a logical framework for understanding, analyzing, and comparing features of multi-device UIs [28]. More recently, Paternò published an in-depth survey and classification of research in this area [27]. However, despite many progresses, there are still important challenges to overcome [6].

The anthropological concept of proxemics is also important to this research. It identifies the culturally dependent ways in which people use interpersonal distance to understand and mediate their interactions [11]. Likewise, users should expect increasing connectivity and interaction possibilities as they bring their devices closer together [10]. Saul Greenberg has been one of the most significant contributors to this area. His team developed a *Proximity Toolkit* to test multiple proxemic-aware applications [17] and *GroupTogether*

to enable co-located collaboration across multiple devices by using sensors placed in the devices and in the environment to capture the relationship between users and their devices [18]. They also introduced the *Gradual engagement* design pattern, which describes how to design interfaces that gradually engage the user by disclosing connectivity and information exchange capabilities as a function of inter-device proximity across three stages [16]. In order to determine the proxemic relationships between multiple devices to enable association and interaction across them, we also developed an indoor positioning system (IPS) along with our framework based on *Wi-Fi* and *Bluetooth Low Energy* after carefully studying existing solutions [2].

3 SOLUTION

We developed the *Yanux* framework to support the automated distribution of UI elements across multiple co-located devices. However, users should be able to easily override the choices that were made for them. Besides that, collaboration should also be fostered in an environment where multiple users and devices meet. This section summarizes the technical aspects of the framework.

3.1 Architecture

Figure 1 shows a diagram of the framework's architecture. The components at the bottom are server-side components (*IPS Server*, *Yanux Auth*, *Yanux Broker* and *Yanux IPS Bridge*). The devices that run applications based on the framework appear on top.

Each device can host multiple applications (*Apps*), which access the framework's services through a library (*Yanux Coordinator*) that abstracts lower level details and provides tools to deal with component distribution and manage the application state. Application instances may also communicate with the *Yanux Broker* by establishing a connection using the *Feathers Client* library or *Socket.io*. The *IPS Client* and *Yanux Orchestrator* run in the background on each device and are shared by all applications.

As for the arrows connecting the components, a single-sided arrow means a request is made from the source component to the target component. Double-sided arrows represent that a bidirectional channel is kept open between the two components once the communication is established from a client component, on one of the devices, to a server component.

More information, documentation and the repositories for all of the components of the framework can be found at <https://yanux-framework.github.io/>.

3.2 Yanux Auth

We need to keep track of the *applications*, *developers* and *users* that are using the *Yanux Framework*. Therefore, *Yanux Auth* consists of a website, as well as related authentication and authorization services. It implements an *OAuth 2.0 Authorization Server* [12] with PKCE (Proof Key for Code Exchange) [1] support that issues access tokens used by the client applications to make requests to other components on behalf of each user. A *Resource Server* was also implemented to expose a service to check the validity of an access token as well as a standard *OpenID Connect* endpoint [29].

Figure 1: YanuX Framework Simplified Architecture

3.3 YanuX Broker

We need to keep track of the UI state across devices. Therefore, the *YanuX Broker* exposes *JSON* (JavaScript Object Notation) objects that should be used by applications to store the global UI state. The application instances on each device can then manipulate and subscribe to changes made to those objects. Within the context of our framework, those objects are called *resources*. Each user can have multiple *resources* stored for each application. It is also possible to share *resources* with other users to enable collaboration.

The *YanuX Broker* supports the submission of *events* because there are some interactions that do not translate well to direct changes to the global UI state and the re-rendering of client application instances on each of the devices based on the propagation of those changes. Each event should have an associated name, payload (a *JSON* object) and the identifier of the *resource* that the user is currently subscribed to. The event is sent to any instances that are subscribed to the same *resource*.

The *YanuX Broker* is also responsible for aggregating data coming from the *YanuX IPS Bridge* into per-user proxemic states and keeping subscribing application instances up-to-date. The proxemic states can be fed to the *YanuX Coordinator* library to determine which UI elements should be shown. When a user is subscribed to a shared *resource* its proxemic state is shared with the same users.

The *YanuX Broker* exposes its services through a *REST API*: `http://j.mp/yanuxbroker`. However, the same set of services are also made available to *Feathers* or *Socket.io* compatible clients. These allow the server to push events to connected clients, which is essential for interactive applications.

3.4 YanuX Coordinator

The services provided by the *YanuX Broker* can be directly accessed using any of the previously mentioned options. However, we have written in *TypeScript* a helper library called *YanuX Coordinator*, which makes it easier to access the *YanuX Broker* from applications based on Web technologies. It also offers non-trivial functionality that is not be easily re-implemented.

The library takes care of lower-level details so that third-party developers can focus on building their own applications. Developers only need to provide the authentication token, which they have acquired from *YanuX Auth*, and to register callback functions for the events that the server can push to connected clients. Depending on the type of event, developers may program their applications to simply change a minor part of the UI or completely re-render it.

The API of the *YanuX Coordinator* can be summarized as follows:

- **constructor(brokerUrl, localDeviceUrl, clientId, credentials):** The constructor that creates a *Coordinator* object with the details needed to connect to the *YanuX Broker*.
- **Properties:**
 - **client:** Client application that is connected to the broker.
 - **device:** Device running the current application instance.
 - **instance:** Local instance of the application.
 - **proxemics:** Proxemic relationships of the devices the user has access to, i.e., including those that are available via resource sharing with other users.
 - **resource:** Default resource of the user on the current app.
 - **subscribedResourceId:** Id of the subscribed resource.
 - **user:** The user using the current application instance.
- **Methods** (arguments with ? have a default value):
 - **createResource(resourceName?):** Creates a new resource.
 - **deleteResource(resourceId):** Deletes a resource.
 - **emitEvent(value, name):** Emits an application event.
 - **getActiveInstances():** Gets active instances that the current user has access to, i.e., including those that are available via resource sharing with other users.
 - **getInstances(extraConditions?):** Gets instances that the current user has access to, i.e., including those that are available via resource sharing with other users.
 - **getProxemicsState():** Gets the proxemic relationships of the devices the user has access to, i.e., including those that are available via resource sharing with other users.
 - **getResourceData(resourceId?):** Gets a resource's data.
 - **getResources():** Gets the resources that the user currently has access to, i.e, including shared resources.
 - **init():** Initializes the connection to the broker.

- **isConnected()**: Indicates if the Coordinator is connected.
- **logout()**: Logs out from the Broker.
- **setComponentDistribution(components, auto?, instanceId?)**: Sets the distribution of UI components.
- **setInstanceActiveness(active)**: Sets if the current instance is active, i.e., if it is being used.
- **setResourceData(data, id?)**: Sets a resource's data.
- **shareResource(userEmail, resourceId?)**: Shares a resource with a user.
- **subscribeEvents(subscriberFunction)**: Subscribe to application events.
- **subscribeInstances(subscriberFunction)**: Subscribe to changes made to instances.
- **subscribeProxemics(subscriberFunction)**: Subscribe to changes made to the proxemics that user has access to, i.e., including those that are available via resource sharing with other users.
- **subscribeReconnects(subscriberFunction)**: Subscribe to reconnection events.
- **subscribeResource(subscriberFunction, resourceId?)**: Subscribe to changes made to a resource.
- **subscribeResourceSubscription(subscriberFunction)**: Subscribe to changes made to the resource subscription, i.e., which resource is subscribed by the user.
- **subscribeResources(subscriberFunction)**: Subscribe to changes to made to the resources that a user has access to, i.e., owned or shared with.
- **unshareResource(userEmail, resourceId?)**: Unshares a resource that was shared with another user.
- **unsubscribeEvents(), unsubscribeInstances(), unsubscribeProxemics(), unsubscribeReconnects(), unsubscribeResource(), unsubscribeResourceSubscription(), unsubscribeResources()**: Unsubscribe from the corresponding subscriptions mentioned above.
- **updateInstanceActiveness()**: Determines if the current instance is being used and sets its activeness accordingly.

More details are available here: <http://j.mp/yanuxcoordinator>.

3.4.1 Resource Management. Since the framework can store multiple application states (*resources*) per user and application. This can be useful for multi-tasking, e.g., multiple opened documents, seamlessly switching back and forth between multiple videos, or participating in multiple conversations. *Resources* can also be shared with other users to enable collaboration in the same space. For instance, we can envision collaborative multi-device document editors, classroom applications or digital canvases.

Therefore, we have developed a *Web component* named *YanuX Resource Management Element* to assist developers with the management of *resources* in an application's UI (see Figure 2).

The list of *resources* owned by or shared with a user are fed into the *Web component*. They are listed in a drop-down list and an event is triggered when users select a resource so that developers can instruct the *YanuX Coordinator* to retrieve and subscribe to it.

The buttons below the drop-down list allow users to create, rename, share or delete a resource. There is a second drop-down that will be populated with the e-mail of the users with whom the resource has been shared. The owner is able to click on the button

Figure 2: *YanuX Resource Management Element*.

next to the list to stop sharing the resource with the currently selected user. These actions show a dialog box asking for extra input or confirmation. Once confirmed, the *Web component* fires an event which let developers know that they should make the relevant *YanuX Coordinator* API calls to actually perform the operations.

The *YanuX Resource Management Element* API can be summarized as follows:

- **HTML Attributes:**
 - **resources:** The resources that the user has access to, i.e., including shared resources.
 - **selectedResource:** The currently selected resource.
 - **selectedResourceId:** The Id of the selected resource.
 - **userId:** The Id of the current user.
- **Custom Events:**
 - **create-resource:** The *detail* property contains the *resourceName* of the created resource.
 - **delete-resource:** The *detail* property contains the *resourceId* of the deleted resource.
 - **rename-resource-name:** The *detail* property has the renamed *resource*, its *resourceId* and its new *resourceName*.
 - **resource-selected:** The *detail* property contains the selected *resource* and its *resourceId*.
 - **share-resource-email:** The *detail* property contains the *resource*, its *resourceId* and the *userEmail* of the user with whom the resource was shared.

More details are available here: <http://j.mp/yanuxresman>.

3.4.2 Component Distribution. Another key aspect of *YanuX Coordinator* is the automatic distribution of UI components. The *YanuX Orchestrator* gathers information about each device's capabilities and sends it to the *YanuX Broker*. Meanwhile, the *YanuX Broker* keeps track of the connected instances of each application and the *YanuX Coordinator* is also able to determine if an instance is inactive, i.e., it is running in the background.

Developers need to add an object to their application that follows our *JSON-based DSL* (Domain Specific Language), as defined here: <http://j.mp/yanuxcompres>. The name of the properties of the object are the unique names of the UI components of the application. For each component, the developer must use our *DSL* to define restrictions and preferences that will be taken into account when determining whether a component should be visible.

The API of our *ComponentsRuleEngine* can be summarized as follows:

- **constructor(localInstanceId, localDeviceUuid):** Initializes some properties of the distribution engine.

- **Properties:**
 - **currentComponentsDistribution:** Current distribution of UI components.
 - **instances:** Instances considered by the algorithm.
 - **localDeviceUuid:** UUID of the local device.
 - **localInstanceUuid:** Id of the local instance.
 - **proxemics:** Proxemic relationships of the devices the user has access to, i.e., including those that are available via resource sharing with other users.
 - **restrictions:** *DSL* that imposes restrictions on the distribution of components.
- **Methods:**
 - **run(ignoreManual?):** Runs the distribution algorithm. *ignoreManual=true* resets the distribution to automatic.

More details are available here: <http://j.mp/yanuxcompuleng>

The automatic distribution of components strives to come up with the best solution. However, users should be able to override it because they might prefer a different distribution. Therefore, we have created a *Web component* named *Yanux Components Distribution Element* that allows developers to give the control over the distribution of UI components back to users (see Figure 3).

Device: Laptop Instance: Instance 1					
Device	Video Call	Camera	Chat Messages	Chat Input	Auto
Laptop (Instance 1)	☒	☐	☐	☐
Laptop (Instance 2)	☐	☐	☒	☒
Tablet	☐	☒	☒	☐
Smartphone	☐	☐	☐	☒

Figure 3: *Yanux Components Distribution Element*

The names of the device and of the instance where the element is placed are displayed at the top. Figure 3 shows a total of four applications instances running on three distinct devices and four components. The headers of the 2nd to 5th columns display the name of the components while the rows below contain check boxes reflecting the distribution of components across the active application instances. Users can use them to choose if a component should be shown on the corresponding application instance listed in the 1st column. When that happens, the *web component* emits an event.

The 6th column has buttons that indicate if the distribution for a certain application instance was determined automatically (pressed green state) or if it was set by the user (unpressed red state). If a user changes the distribution of components, the corresponding button will become unpressed and red. Moreover, when a user presses one of those buttons the *Yanux Components Distribution Element* generates an event signaling that the user wants the distribution of the UI components of the corresponding instance to be automatic.

The *Yanux Coordinator's* distribution algorithm should be invoked whenever there are changes in the proxemic relationships of co-located devices or in the available instances, when there is a

manual change in the distribution of components, or when a users requests to reset the distribution of an instance. The algorithm gives priority to the distribution made by the user.

Otherwise, it will take into account the restrictions defined by the developer, the proxemic relationships between devices, whether each application instance is active, and the capabilities of the devices running those instances. The algorithm runs independently on each application instance and returns a *JavaScript* object with a *boolean* property for each component that indicates whether it should be shown. It is up to the developer to interpret these values.

The *Yanux Components Distribution Element* API can be summarized as follows:

- **HTML Attributes:**
 - **componentsDistribution:** Distribution of UI components.
 - **instanceId:** The Id of the current instance.
- **Custom Events:**
 - **reset-auto-components-distribution:** The *detail* property contains the *instanceId* that had its distribution reset.
 - **updated-components-distribution:** The *detail* property contains the *instanceId*, the name of the *component*, the *checkboxChecked* status and the updated *componentsDistribution*.

More details are available here: <http://j.mp/yanuxcompdist>

3.5 Indoor Positioning System (IPS)

The framework needs to have an updated perspective of the devices available in the surrounding environment. It relies on the awareness of the devices' proxemic relationships, specifically the distance, orientation, and identity dimensions [10]. Since there is no readily available solution that enables us to capture that information, we had to develop our own.

The *IPS Client* is available for *Android* and *Linux*. It scans for *BLE* (Bluetooth Low Energy) beacons and *Wi-Fi* access points, and sends its findings to the *IPS Server* along with the orientation reported by the device's sensors. The server estimates the device's position and publishes the results to a *WAMP (Web Application Messaging Protocol) Router* running besides it [37]. Any interested party can subscribe to those position updates.

The *IPS Server* supports radio map fingerprinting and proximity sensing techniques that apply machine learning algorithms to predict a device's absolute position in an area and the relative position to *BLE* beacons, respectively. Trilateration is also supported and it applies the method of least squares to estimate a device's position based on the distance to the known location of at least three *BLE* beacons. Moreover, the server uses fuzzy logic to decide what is the most appropriate positioning technique in a specific situation. By following this procedure, the system's performance is expected to be at least equal to the performance achieved by the best performing algorithm [24].

3.6 Yanux IPS Bridge

The *Yanux IPS Bridge* integrates the framework with the positioning system by subscribing to the *IPS Server* through the *WAMP* protocol [37]. It tracks successive events from the same device and passes them through an *exponential moving average* filter to smooth out

any errors before sending the measurements to the *YanuX Broker* for further processing.

Proxemic relationships are established between devices that belong to users that have access to the currently selected *resources* (i.e., both owners and users that the *resources* have been shared with), if their positions are within 3 meters of each other and their orientations deviate by less than 90 degrees. These values were chosen based on empirical experiments that were performed during the development of the solution.

3.7 YanuX Orchestrator

The functions may be the same but multi-device applications must run on a broad variety of devices with different input and output modalities [26]. Screens may range from the tiny ones found on smartwatches, to large TV screens, while there are devices that may not have a screen, e.g., a smart speaker. Input may come from a T9 keypad, a touchscreen, a mouse, or a physical QWERTY keyboard.

A single UI solution will most likely not fit the full range of possibilities [36]. The UI of these applications should be responsive and adapt to the devices where they are running [8]. Therefore, we developed the *YanuX Orchestrator* to gather information about the capabilities of the devices, i.e., displays, speakers, microphones, cameras, input devices, sensors and other details.

The *YanuX Orchestrator* is available for *Android* devices and *Linux* PCs. It runs in the background to continuously update the *YanuX Broker* because capabilities can change over time, e.g., a monitor can be connected to a laptop. These capabilities can then be taken into account by *YanuX Coordinator* distribution algorithm. Table 1 summarizes the information that can be gathered or inferred about the devices.

4 CONCLUSIONS AND FUTURE WORK

We have presented how the *YanuX Framework* provides useful abstractions and tools to allow developers to create applications that run across multiple co-located devices. We provide tools for the automatic distribution of the UI based on the capabilities of the devices running the applications, on restrictions defined by the developers, and on relationships established between the co-located devices. Notwithstanding, we allow users to easily override the distribution of the components according to their preferences. We have also enabled users to manage and share multiple application states (*resources*) to design environments where multiple users can interact and collaborate.

However, there are still more improvements that we wish to make. We will need to continue refining the *YanuX Broker* and *YanuX Coordinator* to better support a wider range of scenarios. In the future, we intend to expand the collaboration capabilities and to support multi-tasking involving multiple applications. We envision that the *YanuX Orchestrator* will listen to events sent from the *YanuX Broker* and react accordingly by managing applications, splitting the screen for simultaneous multitasking in public displays, or dealing with cross-device interaction gestures. We also intend to improve the positioning system and to take better advantage of its absolute positioning capabilities. For instance, a radar widget could be used to represent devices and the components currently

Table 1: Extracted Device Capabilities

Name	Description
Type	<i>String</i> , e.g., <i>desktop</i> , <i>laptop</i> , <i>tablet</i> , <i>smartphone</i> or <i>smart TV</i>
Display	Single Object or Array
Type	<i>String</i> , e.g., <i>internal</i> , <i>external</i> or <i>touchscreen</i>
Orientation	<i>String</i> , e.g., <i>landscape</i> or <i>portrait</i>
Resolution	<i>Array[Integer]/pixel</i> , e.g., 1 to ∞
Bit depth	<i>Integer/bit</i> , e.g., 1 to ∞
Refresh Rate	<i>Float/Hz</i> , e.g., 0 to ∞
Size	<i>Float/millimeter</i> , e.g., 0 to ∞
Pixel Density	<i>Integer/pixels per inch</i> , e.g., 0 to ∞
Pixel Ratio	<i>Float</i> , e.g., 0 to ∞
Virtual Resolution	<i>Array[Integer]/pixel</i> , e.g., 1 to ∞
Speakers	Single Object or Array
Type	<i>String</i> , e.g., <i>loudspeaker</i> or <i>headphones</i>
Channels	<i>Integer</i> , e.g., 1 to ∞
Bit depth	<i>Integer/bit</i> , e.g., 1 to ∞
Sampling Rate	<i>Float/Hz</i> , e.g., 0 to ∞
Camera	Single Object or Array
Type	<i>String</i> , e.g., <i>main</i> , <i>telephoto</i> , <i>wide-angle</i> , <i>selfie</i> or <i>webcam</i>
Resolution	<i>Array[Integer]/pixel</i> , e.g., 1 to ∞
Bit Depth	<i>Integer/bit</i> , e.g., 1 to ∞
Refresh Rate	<i>Float/Hz</i> , e.g., 0 to ∞
Microphone	Single Object or Array
Channels	<i>Integer</i> , e.g., 1 to ∞
Bit Depth	<i>Integer/bit</i> , e.g., 1 to ∞
Sampling Rate	<i>Float/Hz</i> , e.g., 0 to ∞
Input	<i>Array[String]</i> , e.g., <i>keyboard</i> , <i>mouse</i> , <i>stylus</i> , <i>touchscreen</i> or <i>speech input</i>
Sensors	<i>Array[String]</i> , e.g., <i>GPS</i> , <i>accelerometer</i> , <i>gyroscope</i> , <i>compass</i> , <i>barometer</i> , <i>light</i> or <i>proximity</i>

associated with them, with redistribution of components being accomplished through drag-and-drop.

We intend to use *YanuX* in the development of applications that respond to societal challenges, besides continuing to develop prototype applications from which we have already received encouraging feedback [31, 32]. In fact, we have recently concluded a user study supported by an application developed with the framework (see the following video: <https://youtu.be/0q4qtyWWCpM>). In addition to continuing to assess how people can benefit from applications running across multiple co-located devices, it is equally important to understand if developers can easily use our framework to build their own multi-device applications. Therefore, we also intend to conduct developer focused studies to evaluate the usability and acceptance of the framework from that point of view.

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