A Web Browser-based Interaction Framework for Mobile Opportunistic Applications

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ABSTRACT

Opportunistic networking is one way to realize pervasive applications while placing little demand on network infrastructure, especially for operating in less well connected environments. In contrast to the ubiquitous network access model inherent to many cloud-based applications, for which the web browser forms the user front end, opportunistic applications require installing software on mobile devices. Even though app stores (when accessible) offer scalable distribution mechanisms for applications, a designer needs to support multiple OS platforms and only some of those are suitable for opportunistic operation to begin with. In this paper, we present a web browser-based interaction framework that 1) allows users to interact with opportunistic application content without installing the respective app and 2) even supports users whose mobile OSes do not support opportunistic networking at all via minimal stand-alone infrastructure. We describe our system and protocol design, validate its operation using simulations, and report on our implementation including support for six opportunistic applications.

1. INTRODUCTION

Mobile opportunistic networking allows designing applications that share and relay data between smart devices without the need for network or backend infrastructure. This makes such applications suitable for environments with very limited or not (always) available Internet connectivity. Instead of detouring information to be shared via a “central” repository in the cloud that maintains user accounts, state information, and the actual contents, opportunistic applications are distributed in nature with state spread across devices. State updates and content sharing happen using message exchanges via short-range radio such as WLAN or Bluetooth when two or more nodes come into radio range (contacts). In-between contacts nodes “carry” the messages as they move around so that spreading takes place via both relaying and mobility. The resulting connectivity of the network is a function of the effective radio range, node density, and node movement.

A number of systems were designed for opportunistic networks to offer various kinds of asynchronous messaging abstractions to applications, including (but not limited) to: The Haggle architecture [56] has been the basis for different flavors and system implementations [61][43] that offer asynchronous communication, data distribution, and pub/sub primitives to applications such as webmail, and content sharing. MobiClique [49] is a platform and API designed based upon the Haggle architecture and supports impromptu interactions between nearby users with three initial applications: mobile social networking, asynchronous messaging, and newsgroups. The 7DS system [37] offers an asynchronous object-based synchronization mechanism for mobile nodes without the Internet to support applications such as file sharing and bulletin boards. Helgason et al. [22] devised a platform plus API for content sharing applications including gateway functions to interact with content on the Internet. Their applications include mobile social networking, local quizzes, and sensor data relaying. Higgins et al. [24] developed a communication platform that integrates diverse networks including (Bluetooth-based) opportunistic ones and offers a socket-style abstraction for applications such as a file system, email, and sensing. The ShAir platform [17] offers mobile-to-mobile content sharing using opportunistic networking along with an API; applications include file sharing, photo, and news sharing and shared drawing, among others. Finally, the delay-tolerant networking architecture [18] and its protocol specifications [8][57] have led to a number of implementations that also support mobile Android devices. Those include the SCAMPI mobile opportunistic networking platform [31] and IBR-DTN [15], with numerous applications such as (voice) messaging, and photo sharing, among others.

In addition to the apps mentioned above, numerous stand-alone opportunistic applications have been developed, for content distribution (e.g., PodNet [34], NetInf [12]), geo-based content sharing (e.g., Hovering Information [66], Floating Content [45, 46], Locus [63]), multimedia messaging (e.g., DT-Talkie [27] or streaming (e.g., [39]), and text messaging (e.g., Twimight [25], XMPP [30], Firechat1).

Both the above mobile platforms and applications share the requirement that users need to get and install the applications first before they can use them— or even gauge if the applications would have interesting content to offer. This is in stark contrast to typical content access in the Internet, where the ubiquitous web browser is the only tool a user typically needs to explore most content and service offerings. While there is a clear tendency for services to also provide mobile apps for more convenient service access from mobile devices, those apps are usually in addition to browser-based access, so that a user who finds an offering interesting can take another step to improve convenience and user experience. But the user can take this decision after she has seen what the respective service has to offer. Not having web-based access to screen what is available may severely limit a user’s inclination to even try out an application.

1https://opengarden.com/firechat
This burden is even worse for opportunistic applications compared to Internet-based ones that would depend on the installation of an app: opportunistic platforms or applications are not only needed for content access, but they also serve to create the very network via which any information is exchanged in the first place as there is no independent Internet infrastructure to rely on. A user not installing an app due to lack of incentive will thus also not contribute to the network and harm connectivity for other users.

In this paper, we explore making content of opportunistic applications available to all users, that is, those who have installed an opportunistic application (who we refer to as opp users) as well as those who haven’t (who we call legacy users). To achieve this goal, we devise a generic opportunistic application framework that enables content access via web browsers. In particular, we make the following contributions: 1) We dissect application logic for opportunistic operation to allow externalizing a subset of the functionality to support web-based access in section 2. 2) We devise a system and protocol framework that allows applications to provide code for creating, reading (presenting), and writing (responding to) application messages along with the messages themselves or the application distribution (section 3). 3) We implement a runtime system and an extended API and integrate it with two different opportunistic communication platforms, SCAMPI [31] and IBR-DTN [15], which support the above functions (section 4). We also develop a simple NULL platform running on a Linux-based WLAN access point with local storage (e.g., a Raspberry Pi or Intel Edison) that supports locally autonomous networking without the aid of an sophisticated opportunistic networking stack. 4) We demonstrate its operation by enhancing three opportunistic content sharing applications (section 5). 5) We evaluate the potential gains and analyze the incurred overhead using simulations and measurements in section 6.

2. APPLICATION AND MESSAGING MODEL

The messaging model that we use can be derived from the fundamental properties of distributed systems and opportunistic store-carry-forward networks. In general, distributed systems are designed to establish a globally consistent state in multiple independent entities through message exchanges. This is shown in Figure 1, where a state change $S_0 \rightarrow S_1$ in $N_2$ is propagated to the other entities in the system through messaging. This process takes place from time $T_1$ to $T_3$, which is the time it takes for the message to propagate to all other entities. During this time the system is in a globally inconsistent state, and the process of reaching a consistent state is called equilibration. The fundamental problem of distributed systems design is to ensure that the equilibration process results in globally consistent states in the face of potential concurrent and parallel state transitions in the entities.

The CAP conjecture [6] is a useful tool for thinking about the fundamental properties of distributed systems. The major insight to be gained from CAP is that when facing partitions (P), a distributed system design can trade availability (A) against consistency (C). Strict consistency can be enforced in some systems by a global locking mechanisms, but it leads to no availability when the system is partitioned and the lock cannot be acquired. Consensus mechanisms employing quorums alleviate this by requiring only a subset of the entities to agree on state changes. This effectively leads to the larger part of a partitioned system to remain available, at the expense of the other part having no availability and an inconsistent view of the global state. Mechanisms such as using soft state and caches closer to the clients ensure availability in the case of partitions, but can lead to a globally inconsistent state and problems when trying to reconcile inconsistent states after a partition ends. This essentially buys more availability at the cost of going from strict consistency to eventual consistency. In all cases, a key assumption in the design of both centralized and peer-to-peer distributed systems is that partitions are transient phenomena, and the system can eventually reach a fully consistent and available state again.

An important observation regarding the CAP formulation is that partitioning is tightly coupled with latency, forming a type of latency-partition duality. This is because in the absence of explicit knowledge about the network, a partition is not distinguishable from a long delay, as illustrated in Figure 2. This forces system designs to use delay thresholds as indicators for partitions, which in turn makes implicit assumptions about the information propagation speed in the network. In particular, it assumes that latencies are in the order of user-acceptable application level transaction times; an assumption that holds in well-connected infrastructure networks where failures are transient conditions.

Opportunistic store-carry-forward networks are composed of pairwise contacts between mobile nodes. This means that the information propagation latency is limited primarily by the inter-contact times between the mobile nodes, and not by the speed of light (and queuing) as in well-connected networks. Combining this with the latency-partition duality, such systems can be seen as being in a constant state of partitioning, causing the breakdown of the underlying assumptions of the mechanisms used to maintain consistency properties in “classical” distributed systems. Another way to state this is that the time for a distributed system built on such a network to equilibrate can be orders of magnitude larger (or even unbounded) than the time scales required by meaningful application semantics. I.e., changes are entering the system significantly faster than the time it takes to reach an equilibrium.

This leads to the need to abandon the idea of global consistency,
and instead build distributed systems that are inconsistent by design. A system that is inconsistent by design requires each entity to build their own locally consistent view of the world based on their own set of observations. In concrete terms, it is the client software’s responsibility to create a locally consistent view or state from the (random) set of messages that is has received.

Messaging is used as a way to transition the state of the entities in distributed systems. This can be written as $m : \Delta(S_x, S_{x+1})$, where $S$ is the state of the system. In other words, a message contains the difference between the two states, which the recipient can apply to its state $S_x$ to transition to the state $S_{x+1}$. This has two major implications: 1) the recipient must be in the given state $S_x$ or the message is useless, and 2) as a result of applying the message, the recipient will be in the precise state $S_{x+1}$. This makes sense in distributed systems that are designed to (periodically) reach globally consistent states.

The above messaging model does not make sense in distributed systems that are inconsistent by design, including opportunistic networks. First, the messages should be applicable in any state, otherwise in a system where every entity is potentially in a different state, most messages would be useless. Second, since the system is not designed to ever reach a globally consistent state, the messages do not need to result in all the recipients moving to the same state, just some locally consistent state.

This leads to a different messaging model, where each message will cause a different state transition from one locally consistent state to another in each receiving entity. This can be written as $N(m) : S_N \rightarrow S_{N'}$, where node $N$ applies message $m$ to transition from the locally consistent state $S_N$ to another locally consistent state $S_{N'}$. We can observe that it must be possible to apply the transition from any state, including the empty state, into some locally consistent state; $N(m) : \emptyset \rightarrow S_N$. This is typically expressed in opportunistic and delay-tolerant networking as messages being self-contained and semantically meaningful.

It is this fundamental property of self-contained messages that we exploit in building our framework. This messaging model further implies that the network will have a large number of these messages (i.e., content), which can be interpreted independently of any specific application state. However, the applications themselves are still required in order to participate in the system. The key idea of our framework is to ship minimal, generic application logic along with the messages, which allows any node a degree of interaction with the system (e.g., view, respond and send) without requiring the specific native application.

From the application perspective, we can describe the framework through the Model-View-Controller (MVC) paradigm, which is widely used both as a conceptual model and an implementation model for systems with (graphical) user interfaces. Figure 3 summarizes the application model of our framework. First, (a) depicts a simple MVC style of a GUI-based application design: A data model $M$ (schema plus actual data) represents the application state as structured data, a view $V$ of this model is rendered to the user via a GUI, and a controller $C$ receives input from the user via the GUI and acts upon the input by modifying the model accordingly (after validating the input). Next, (b) shows a “classical” distributed application that exchanges messages containing the deltas between different states, as described earlier. Finally, in (c) we can see a simple model in which applications exchange complete model information in self-contained messages that allows state-independent interpretation.

3. APPLICATION INTERACTION FRAMEWORK

In this section, we provide a detailed description of the Web as transport and HTML5 for presentation/interaction) so that standard mobile devices can interact with the contents.
Browser-based Interaction Framework. We begin with introducing the ecosystem of the opportunistic network extended with legacy devices (Section 3.1). In Section 3.2 we describe the framework and its functionality at a conceptual level. The heart of the framework is realized by extending opportunistic application messages with a new metadata protocol described in Section 3.3. Section 3.4 provides a detailed description of the framework for a DTN router, including functionalities and interactions between framework components. Section 3.5 briefly describes the enhanced application development process. Finally in section 3.6 we discuss security implication for the framework design.

3.1 Extended opportunistic network ecosystem

In Figure 4 we illustrate the ecosystem of the opportunistic network extended with legacy users and the Liberouter. Opp users communicate between themselves using native opportunistic network software. Liberouter acts as a stationary opportunistic node with large storage space. It also runs the web portal and the Web Browser-based Interaction Framework. Legacy users are able to communicate with opp and other legacy users by connecting to Liberouter and using: (1) web portal to read content available in the network and (2) web interface to generate new content by means of remote code execution.

3.2 Conceptual Model

Conceptually we model opportunistic applications and messages belonging to these applications. Each message is assumed to be self-contained and semantically meaningful. The applications have native clients that are the primary means for generating and consuming the messages. Our goal is to enable non-native generation and consumption of the messages by web browsers through the Web Browser-based Interaction Framework. The consumption goal can be trivially realized by embedding HTML code that describes content of the message. However, this approach does not allow for seamless message exchange between opp and legacy users. Additionally, it also does not separate application state and its presentation making it difficult for app developers. Thus, we model the consumption and generation of messages as transformations of a set of opportunistic messages.

The consumption of messages can be seen as a transformation of opportunistic messages into a view rendered by a web browser, i.e., generation of an HTML page from a set of messages. There are two aspects to this transformation: 1) the individual messages must be transformed into HTML representation, and 2) these individual views must be composed into a coherent application view. For example, a photo sharing application would be composed of a transformation of the individual messages into, e.g., thumbnail views, and a composition of those thumbnails into an application view, e.g., list sorted by the date.

For the first aspect, we define two transformations: message summary and message presentation. The message summary transformation generates a concise view of the message, suitable for inclusion in a listing of a large number of messages. The message presentation transformation generates a detailed view of the message, intended to be displayed on its own to a user who is interested in the message contents. Both transformations are pure functions that take as input the message and generate the presentation as output (e.g., HTML code). The transformations are message type and application dependent, and are expected to be included in the message itself by the original generating application.

Due to the assumption of self-contained and semantically meaningful messages, the message transformations alone already provide a useful view into the messages. However, in many applications there may be further constraints on the display of sets of messages. For example, a message board application should list its messages in time order and possibly threaded by topic. This corresponds to application level logic which would normally be implemented by the native clients. While our immediate goal is not to enable fully fledged applications to be built on top of the framework, it must be possible to apply some degree of application layer composition logic in order for the generated views to be meaningful. To this end we define application presenter transformations.

Application presenter transformations are similar to the message transformations in that they are functions that map a set of inputs into an HTML view to be displayed to the user through a web browser. As input, they take a set of messages (e.g., all messages belonging to a particular application), and optionally some set of state generated by a previously run presenter. For example, a forum application could have one application presenter transformation that processes all forum messages and generates a list of topics. When the user selects a topic, another application presenter transformation would generate a list of all messages within the topic. In general, each application can have an arbitrary number of linked application presenter transformations that can call each other and the message transforms. These transform functions can be published separately (e.g., along with the native client bundle if it is published through the opportunistic network), or included in the messages. In general there may be multiple different versions of the application transform functions published into the opportunistic network, and selecting which one to use is out of scope for this paper.

The generation of messages can take two forms: generating new messages, or responding to an existing message (which may itself be either new message or a response to an earlier message). Both take as input a predefined set of values and compose a message, which is then injected into the opportunistic network by the framework. The difference is that the response transformation also gets as a parameter the message to which the user is responding. The new transformation is application level and can be distributed similarly to the application presenter transformations, while the response transformation can be attached directly to the messages to enable responses to be generated to the particular messages.

3.3 Web Message Interaction Protocol

As a message carries arbitrary type of content, each transformation is assigned to a particular message. Thus, to enable it, we have developed a simple Web Message Interaction Protocol (WMIP) that
Table 1: Web Message Interaction Protocol summary

<table>
<thead>
<tr>
<th>Metadata key</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>bundleType</td>
<td>Indicates content type carried inside the message (see table 2 for list of available values)</td>
</tr>
<tr>
<td>description</td>
<td>Text describing message content</td>
</tr>
<tr>
<td>service</td>
<td>Application name</td>
</tr>
<tr>
<td>system</td>
<td>Opportunistic software name</td>
</tr>
<tr>
<td>icon</td>
<td>File containing application icon</td>
</tr>
</tbody>
</table>

Table 2: Overview of inferred HTML mappings for given bundle-Type

<table>
<thead>
<tr>
<th>bundleType</th>
<th>Inferred HTML presentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>audio</td>
<td><code>&lt;audio&gt;</code></td>
</tr>
<tr>
<td>video</td>
<td><code>&lt;video&gt;</code></td>
</tr>
<tr>
<td>image</td>
<td>thumbnail</td>
</tr>
<tr>
<td>text</td>
<td>text beginning</td>
</tr>
<tr>
<td>app</td>
<td>link</td>
</tr>
<tr>
<td>other...</td>
<td>link</td>
</tr>
</tbody>
</table>

Two units are responsible for consumption of messages, and their arrangement as a part of HTML view. The two latter components enable non-native generation of new messages. Figure 5 shows the framework’s architecture overview.

The Message Presenter tracks content of the router database (router DB), and upon reception of each new message (see (1) in the Figure 5), it initiates the process of message consumption. The process begins with a procession of WMIP data contained in the message. All WMIP data are stored inside the content database (content DB) as a hash map with unique message ID as the key (see (2) in Figure 5). Having completed WMIP data examination, the Message Presenter checks if the message has transformation items embedded. If yes, it executes the summary transformation, and takes its output as the generated HTML code. If the summary transformation is missed, the framework provides a simplified content transformation using value of the bundleType meta key as well as other available keys. Table 2 describes mappings between bundleType meta item value and appropriate message representation as an HTML object for simplified message transformation. If the message does not have any WMIP data embedded, or the framework does not know how to present the message (e.g., unknown bundleType value), the Message Presenter presents the message as a simple link that can be downloaded.

In addition to providing access to the content carried by the messages, the framework can also be used to provide access to native applications. This is because the native applications themselves can be bundled up and sent over the opportunistic network. This makes the network self-sufficient, except for the bootstrap problem of needing the native platform application (e.g., SCAMPI router, or IBR router). To solve this issue, the framework makes native applications published into the opportunistic network available to web browser users. If a received message has bundleType value of “app”, the Message Presenter extracts the binary contained in the message and makes it accessible for download via the web browser (see Figure 5).

The Application Presenter’s primary role is to arrange an appropriate presentation of message content from the application point of view. For instance, it may structure the web page view by dividing it into tiles where each tile is filled by the output generated by a summary transformation. Apart from arranging web page display, the Application Presenter provides also graphical components (e.g., buttons, links) that allow the user to actively interact with the content (i.e., respond to existing/generate new messages). These graphical items are linked to the Web Interaction Manager (see (4) in Figure 5), which is responsible for handling of message access events.

The Web Interaction Manager component listens for message access events. If the user invokes the event to see details of the particular message content, the Web Interaction Manager performs a presentation transformation and returns output produced by it to
the Application Presenter that provides content view to the user (see (4)–(6) in Figure 5). Furthermore, Web Interaction Manager also allows the user to generate new application content by either responding to the existing message, or creating a completely new message. When the message generation event is invoked by the user, the Web Interaction Manager executes response/new transformation to respond to the existing/create a new message. The transformation outputs an HTML form that is returned to the Application Presenter unit for display to the user (see (4)–(6) in Figure 5). The user must then fill it in, and send it back to the web server where it is validated by the Web Interaction Manager component, and finally sent to the Message Generator unit (see (4) and (7) in Figure 5).

The Message Generator component listens for incoming content generation requests that are sent by the Web Interaction Manager. Upon reception of such a request, the Message Generator creates a new message based on data received from the Web Interaction Manager, and moves the newly created message to the local router database (see (8) in Figure 5), so that it can spread in the network.

3.5 Enhancing opportunistic applications for legacy users

Development. To enhance an opportunistic application for legacy users access, an app developer must implement transformations he intends to use in the application. Among all possible transformations, only the application presenter transformation is the mandatory one. Implemented transformations must be embedded into application messages as meta data.

Testing. To facilitate the development process, we have also implemented a simple transformation testing environment. It allows the app developer to test correctness of his implementation by: (1) executing the transformation in it and (2) verifying that HTML view generated by the transformation is coherent with the application design.

3.6 Security considerations

Our security considerations cover three issues: (1) secure execution of transformations, (2) message authentication, and (3) providing access to encrypted content for legacy nodes.

Threat model. The threats that we are concerned are that an adversary: (1) disrupts framework functionality by executing malicious code and (2) impersonates another user by sending a message that masquerades its originator for another user.

Secure execution of transformations. Execution of transformations of unknown origin poses a serious threat to the secure functioning of the Web Browser-based Interaction Framework, as they may include system calls causing disruption of the framework functionality as well as leakage of data contained in other stored messages. This threat model motivates implementation of the file system level isolation and the system calls filtering (see section 4 for details).

Message authenticity.

We address the threat of another user impersonation by providing message authenticity mechanisms. Message authenticity requires providing a binding between an identity of the message sender and his/her personal public key. In this work, we assume availability of such a public key distribution system for legacy nodes (e.g., the SocialKeys, or PeerShare). Verification of message authenticity can be realized either on the framework side, or in the web browser. In case of the framework side authentication, the framework itself verifies message signatures using public keys available in its storage. The browser side verification assumes that public keys are accessible in the browser for the web application (see section 4 for implementation details).

Encrypted message content access. In the framework design we make the assumption that content carried inside messages is unencrypted, thus easily accessible by the framework. However, we argue that in the future legacy users experience can be further enriched by providing them also access to the content encrypted messages. To do this, we assume availability of cryptographic keys in legacy users’ nodes which are either delivered via some key distribution system, or derived by legacy users by means of Password-based Cryptography. Since the message content should be accessible only to users that have an appropriate key, encrypted messages must be decrypted inside the browser (using either the Web Cryptography API, or specialized JavaScript module fetched from the framework). Finally, the transformations of decrypted messages must also be executed inside the browser (thus they must be written in JavaScript), so that they can be directly displayed to the legacy user without the necessity to interact with the framework.

Communication mode and privacy considerations. The current framework design assumes that all messages stored in the router DB should be accessible for the legacy users. This assumption holds well for all applications in which users target their messages not at a particular recipient, but at a group of recipients. Consequently, provided that access to the recipient group is open, legacy users can read all messages for the group using the framework. On the other hand, there are also opportunistic applications (e.g., Whisper) which depend on user-to-user communication model. In such a use case, the framework cannot give access to the message for the legacy user who is not the recipient of the message, as it would violate user privacy rules. For these group of applications, the current framework needs to be modified to support addressing scheme for legacy users. This feature can be realised by generating a random endpoint identifier on the first connection to the framework and storing it persistently in the web browser as a cookie. As a result, the framework may use cookie to identify the legacy user and grant access only to his/her private messages.

4. PLATFORM INTEGRATION

We now present the implementation of the Web Browser-based Interaction Framework, and its integration with six different applications. Of SCAMPI open sourced applications, we provide web version of GuerrillaPics, GuerrillaTags, and PeopleFinder, while of IBR-DTN applications, we extend Whisper, Talkie, and Sharebox.

4.1 Framework

We implemented Web Browser-based Interaction Framework, as per Section 5, as a set of PHP extensions, and two native applications. The Message Presenter component is developed in standard Java. It parses newly received messages by the opportunistic network router, and stores their content as a hash map inside the Redis (acting as the content DB). Text items contained in the message are stored directly in the Redis, while binary items are written to the framework’s persistent storage, and only their access paths are stored in the Redis.

The Application Presenter consists of the set of PHP scripts that: 1) communicates with the Redis to learn which application’s con-

Implementation of this part is still ongoing.

Redis: [http://redis.io/](http://redis.io/)
tent is available and 2) arranges presentation of content generated by transformations in the web browser.

The Web Interaction Manager is a set of three PHP scripts. The presentation.php script which internally calls the presentation transformation is executed when the user wants to obtain a detailed view about the particular message. The new.php and generate.php scripts are called in case of generating a response to the existing message, or a very new message. The new.php internally calls the response/new transformations and returns the web form generated by them to the Application Presenter, so that it can be shown to the user. The generate.php script acts as a form handler that processes data submitted in this web form, and sends them to the Message Generator for the message creation. To enable access to the whole content associated with the particular message in the Redis, all these scripts are executed with the Redis message key as the URL parameter.

The Message Generator is the native opportunistic router application that reads data submitted by the Web Interaction Manager, and using opportunistic router API it transforms them into an appropriate message and publishes in the opportunistic network.

Figure 6: Screenshot of the Web Browser-based Interaction Framework presenting native opportunistic applications that can be downloaded on a device and applications having content stored on it.

In our implementation there are no constraints on data types that can be attached to the message as part of the WMIP protocol described in the Section 3.3. The only requirement is that if an attached item is a Java serialized class, such a message must also carry a “.class”, or JAR file implementing the class. In such cases, the Message Presenter dynamically loads attached data, transforms it to JSON, and stores it in the persistent storage.

The transformations are implemented in Python, and must follow basic transformation design guidelines described in Section 3.2. Furthermore, to guarantee access to whole message content, the transformation is always executed with the Redis’ message key as the command line argument. Aiming to guarantee a high level of user experience, the Web Browser-based Interaction Framework gives the transformation access to the Bootstrap library. Therefore, the transformation can generate a sophisticated HTML presentation of the message, while the message itself does not need to carry additional CSS styling files as meta data. To further improve user experience, the framework provides real-time content updates by means of the WebSocket Protocol [19] that is implemented using the socket.io library. In order to prevent transformation crash caused by making a call to the library that is not available in the framework, the framework provides the transformation the list of all libraries available to the transformation. As a result, the transformation can check if the non-standard library call is available, and if it is not, the transformation can make a fallback to a different call.

File system level isolation constrains transformations to access only data contained inside the message and parts of the content DB that are related to the message. The framework realizes it by: (1) creating a temporal directory and inserting into it all data carried inside the message, (2) binding external resources (i.e., content DB) required by the transformation to the temporal directory (using mount system call), (3) isolating other file system resources from the transformation (by means of chroot call). We realize system calls filtering using the seccomp-bpf facility [10]. It allows to whitelist a subset of system calls that a transformation has the permission to execute [1]. Calling of a system method that has not been whitelisted causes termination of the transformation process. Since the transformation should be given access to all data carried by the message, our seccomp-bpf profile allows the execution of only system calls that open and operate on files. For system administrators concerned with chroot vulnerabilities, it is trivial to further enhance sandbox design by replacing chroot with pivot_root system call [44]. Unlike chroot, pivot_root confines the process into a completely separate root file system, thus even if the process manages to escalate privileges and theoretically break away from the file system isolation, it cannot access file system resources outside its directory, as these resources do not exist for it. Further security improvements can be made by defining mount and network namespaces for the sandbox and running transformations inside Linux containers [41]. However, we believe that for our use case it is an overkill.

Browser side message authenticity requires availability of public keys in the browser either via the HTML5’s local storage, device’s persistent storage (e.g., the File API [51]). Both of these solutions are supported by all modern browsers. The authenticity verification process is realized fully inside the JavaScript code via the Web Cryptography API [58]. Although it is preferable from the user privacy point of view to use browser-side message authenticity, the framework-side alternative is the more realistic option due to poor support of the Web Cryptography API among the modern browsers [13].

4.2 Opportunistic router integrations

We integrated our framework with two widely used distributions of opportunistic routers, namely SCAMPI and IBR-DTN. In addition, we also offer an opportunity to use the framework that is not coupled to any distribution of opportunistic router (so called NULL router version).

SCAMPI. SCAMPI is the opportunistic network platform that provides the network layer implementations capable of delivering messages based on store-carry-forward networking. It is implemented as middleware that runs on any platform with Java support, including Android, Linux, Mac OS X, and Windows. It discovers and opens links between nearby peers using Wi-Fi and Bluetooth. These contacts are used to route messages between nodes, resulting

1json-io: https://github.com/jdereg/json-io
2Bootstrap: http://getbootstrap.com
3https://linuxcontainers.org
4https://github.com/rase-/socket.io-php-emitter
5http://linux.die.net/man/2/pivot_root
in an opportunistic store-carry-forward network. The underlying design follow the DTNRG architecture and protocols \cite{8, 57, 13}, but includes a number of extensions to support publish/subscribe messaging, geographically constrained content distribution \cite{29}, and content search mechanisms. Among existing opportunistic network routing protocols, only the Epidemic routing \cite{65} is supported. Namespaced metadata key-value pairs can be attached to the messages to provide application hints to the underlying networking layer.

Applications can be developed to use the communication services provided by the middleware. These applications can either be native (Java) applications on any platform with Java support to run the middleware, or HTML5 web applications on Android. The applications can also be distributed by the middleware without requiring a centralized app store. However, to run the applications, the middleware and the application itself must be running on the device.

Integration of SCAMPI into the framework requires: 1) allowing the framework to access the router DB and 2) implementing new content creation functionality to be in the SCAMPI compliant format. The former one is accomplished by granting the framework access rights to the router DB location, as SCAMPI implements router DB as a set of file system directories. The latter one is achieved by using SCAMPI’s AppLib library that allows to publish new messages to the SCAMPI router instance.

**IBR-DTN.** IBR-DTN is another opportunistic network platform, similarly to SCAMPI working as middleware. It runs on any Linux based operating system as well as on Android and BeagleBone\cite{67}. It discovers and establishes communication links with nearby devices using Wi-Fi, Wi-Fi Direct \cite{67} and Wireless Personal Access Network(IEEE 802.15.4) \cite{26} technologies. Like SCAMPI, the IBR-DTN design follow the basic DTNRG architecture \cite{6, 57, 13}. In addition to SCAMPI, it implements also convergence layers for other underlying network technologies (i.e., UDP over IP, IEEE 802.15.4 LoWPAN). Unlike SCAMPI, IBR-DTN does not offer any application level extensions (e.g., content search mechanisms), however, in addition to the Epidemic routing, it provides other opportunistic network routing protocols, namely PROPHET \cite{35} and Direct Delivery routing.

Applications can be developed to be integrated with the middleware. Currently IBR-DTN provides Java and C++ client libraries that allow applications to communicate with the middleware. For other programming languages, developers must write their own client libraries to communicate over TCP with middleware services.

The process of IBR-DTN integration into the framework is identical to the SCAMPI integration. The only difference is that developers must use: 1) ibrdmlib as a Java library, 2) libapi for C++ development and 3) ibrdm-api for Android.

**NULL router.** In this mode, the framework cannot take any advantage of libraries provided by opportunistic network platform. Framework access to the router DB is achieved in identically as for SCAMPI and IBR-DTN. However, creation of new messages by the framework requires it to: 1) manually build a message (according to the Bundle Protocol \cite{57}) and 2) copy the created message to the router DB.

**Source code.** The source code of the framework implementation together with the enhanced applications will be made available with the final version of the paper.

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13http://beagleboard.org/bone

5. **ENHANCED APPLICATIONS**

We have used the framework to develop enhancements to six existing open-source opportunistic applications working for Android. Among the SCAMPI apps we have extended GuerrillaPics, GuerrillaTags, and PeopleFinder, while for the IBR-DTN router we enhanced Whisper, Talkie, and ShareBox. All of these applications present different types of interactions, but can be enhanced by our framework.

**GuerrillaPics** is a photo sharing application through which users can publish and receive photos using the opportunistic network. The messages are self-contained and stateless, and there are no dependencies between them (e.g., there are no replies or groupings). This is the simplest use-case for the framework: First, an application presenter transformation is used to generate a grid of photo thumbnails. The transformation calls the message summary for each GuerrillaPics message to generate a thumbnail and to get other relevant parameters, in particular, the creation timestamp. These summary elements are then listed in a grid based on time ordering and displayed to the users through the framework. If a user selects one of the summaries by clicking the thumbnail, the message presentation transformation is used to generate a full resolution view. Finally, GuerrillaPics has also the ability to share a new photo through the framework by means of the new transformation.

**GuerrillaTags** is a message board application where messages are not independent as the photos in the previous case, but rather exist in the context of a topic (tag). In this case the summary view is composed from all the unique tags contained in all the messages that belong to the GuerrillaTags service. This is done by the application presenter transformation, which applies the per-message summary transformation to all the GuerrillaTags messages, which produces a list of (duplicated) tags. This list is filtered to remove duplicates in order to produce the topic list. Each unique topic then becomes a summary item. Each topic has its own state entry, which contains the set of bundles which have the particular tag. The presentation view is per-topic, and lists all the messages belonging to the given topic. It is generated by another presenter script by applying the message presentation transformation on all the relevant bundles (as determined from the previously saved topic state), and sorting the resulting list by creation timestamp. This demonstrates how more complex application level logic can operate on message aggregates to generate composite presentations by using the application transformations. GuerrillaTags also includes the ability to post messages through the framework by using the new transformation.

**PeopleFinder** is an adaptation of Google Person Finder system into opportunistic networks. It allows missing persons records to be generated, and notes to be attached to those records. Each message generated by the application contains the record and a set of all notes related to the record known by the sender. The application summary view for the PeopleFinder application is generated from the person records. There may be multiple records for the same person, in which case each is listed separately. The notes attached to a person are displayed in the detail view, which is generated by the message presentation transformation. Adding a new note for an existing record is done through the response transformation, which gets the original record (and notes) as a parameter. The transformation appends the new note to the existing ones, and generates a new aggregate message containing the record and all known notes. New records are generate through the new transformation, which generates a brand new missing person record. Figure 7a shows the native PeopleFinder, and its framework version.
All IBR-DTN applications operate based on unicast communication model. Since the framework currently does not support this type of communication (due to issues described in the Section 3.6), we have modified the applications to make them work on the group communication model.

Whisper is a chat application that allows users to exchange text messages within a particular group of devices. Thus, the messaging model and web view logic are identical to the GuerrillaTags application with the group of devices identifier (group ID) playing the role of the GuerrillaTags’s topic. Finally, Whisper includes additionally the functionality of responding to the current chat discussion through the framework via the response transformation.

Talkie is a walkie-talkie voice chat application through which users share voice messages with a group of devices. The application summary view is built from all unique groups of devices contained among all the Talkie messages. This view is generated by the application presenter transformation. It executes the message summary transformation, which return group ID for each message. After that the application presenter transformation filters out duplicate group IDs. The presentation view is per group ID and contains the list of all voice messages belonging to the given group ID. All these voice messages have the ability to be played out via the message presentation transformation. Finally, Talkie allows users to send new voice messages, or respond within a group of devices via the framework using the new and response transformations. These transformations make use of the JavaScript API for media capture [7] to give web browser access to device’s microphone for voice recording. Unfortunately the media capture API is not currently supported by Safari and Internet Explorer.

ShareBox is a file sharing application in which users exchange pictures or other files within the given group of devices. Similarly to GuerrillaPics, the messages are self-contained, stateless, and do not have any dependencies between themselves. The application summary view (generated by the application presenter transformation) shows a table of message summary views for all Sharebox messages. The message summary view is created by the message summary transformation which shows the size of the message together with the device identifier of its sender and the timestamp. Finally, if the user selects the particular message, the message presentation transformation is used to show the actual files carried inside the given message.

6. VALIDATION

Our web-based interaction framework offers, in principle, content access to legacy nodes (in addition to opp nodes). To achieve this, the framework requires code to be shipped along with message state updates, which incurs overhead. In the following, we first evaluate the overhead and its impact. We then turn our attention to how many legacy nodes could be reached by content if those nodes chose to look at the messages.

6.1 Overhead

To evaluate overhead, we measure the actual message sizes of our implementation for three applications with sample contents. The results are shown in table 3: When using a text messaging app with tiny content, the message size grows almost 50-fold. However, this is due only to the small size of the native messages. If the content size of the application messages increases, the overhead becomes more reasonable. For photo sharing, with small photo size of 65–120KB, including the framework code adds just 5–10% overhead. For the most sophisticated application we looked at, the PeopleFinder, the overhead is roughly factor 15.

<table>
<thead>
<tr>
<th>Application</th>
<th>Native message size</th>
<th>Framework overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Text messaging</td>
<td>350B</td>
<td>16 KB</td>
</tr>
<tr>
<td>Photo sharing</td>
<td>65–120KB</td>
<td>7 KB</td>
</tr>
<tr>
<td>PeopleFinder</td>
<td>2 KB</td>
<td>28 KB</td>
</tr>
</tbody>
</table>

Table 3: Overhead introduced by the framework.

Obviously, the code added via the framework is a function of the complexity of the code required to interpret, render, and construct messages: simpler applications will need less code. The overhead is obviously also a function of the content size so that more elaborate content will cause, even if more complex code is needed, limited overhead only. One can argue that trends in web site complexity and size show that increasing amounts of effort are put into conveying probably roughly the same amount of contents. Thus, adding more sophisticated interaction framework code for a better experience just would mirror what is done on the web.

For opportunistic networks, the most important question is if and how the larger message sizes affect message delivery performance. To this end, we carried out simulations using the ONE simulator [32] with two different mobility models: 1) SPMBM: Shortest Path Map-Based Movement between waypoints chosen from the Helsinki downtown map (4.5 × 3.4km²) [32] for 50 pedestrians moving with speeds \( v = U(0.5, 1.5) \text{m/s} \) without predefined points of interest. 2) SMOOTH: a simple way to model human walks [40] with the map from KAIST scenario (10 × 18km²) and 50 DTN

\[ \text{www.websiteoptimization.com/speed/tweak/average-web-page/} \]
nodes. Our nodes communicate at a net bit rate of 2 Mbit/s with a radio range of 50 m. The nodes use simple epidemic routing [65]. We choose a random DTN node to generate a new message every 12 s, 60 s, and 300 s, referred to as high, medium, and low load, respectively. Messages expire after 5400 s. The message sizes correspond to those for native and framework-enhanced messages for the text and photo sharing applications to pick two extremes. We measure the fraction of nodes that obtain a copy of each message, termed coverage, and plot the average of 10 simulation runs, each lasting for 12 hours.

As shown in figure 8, we find that the overhead of the framework does not notably impact the performance results. The coverage remains the same both for using native application messaging and for the framework-enhanced messaging for the text chat application (top) as well as for photo sharing (bottom). We obtain similar results also for the SMOOTH mobility model, just with much lower coverage rate due to sparser node distribution. This indicates that in the realistic parameter range, the system is not bottlenecked by the contact capacity, and therefore the added messaging overhead does not negatively impact the message distribution.

Further, a maximum message rate limit was also observed in past experiments, which have shown that the per-message overhead of protocol implementations appears to be more dominant in communication performance than the per-byte overhead. This was, for example, found in a comparison of three different DTN bundle protocol implementations [38], particularly for growing the payload size from 10 bytes to 10 KB and beyond. Our own (not yet statistically significant) experiments seem to confirm this. While implementation details play one important role here, there are also systematic aspects to consider: nodes that meet need to exchange vectors which messages they have, decide which ones to replicate, and then perform a forwarding process for each message, which causes per-message overhead. Researchers also found that neighbor discovering and pairing with peers is expensive and takes easily tens of seconds [48] while the sending 20 KB of data takes only 160 ms even assuming just 1 Mbit/s data rate. We therefore argue that the framework overhead is not of substantial importance in practice.

### 6.2 Content Reach

The previous subsection suggests that the overhead introduced by our framework won’t degrade performance for opp nodes. But how well does the framework allow reaching out to legacy nodes? We conduct further simulations to answer this question, using largely the same setup as above. In addition, we introduce two further classes of nodes: access point nodes that, besides running the opportunistic networking protocols, also serve as WLAN access points and run the server side of the interaction framework (cf. figure 5). And legacy nodes that only interact with these access point nodes, but neither with each other nor with regular DTN nodes. We choose the number of legacy nodes to equal (L1), five-fold (L5), or ten-fold (L10) the number of DTN nodes.

Obviously, how many legacy nodes we can reach will depend on the movement patterns of those nodes and where the access point nodes are located, and how they move. However, our simulation results shown in figure 9 hint that we can notably increase the visibility of opportunistic content. For the SPMBM scenario, we find that the content coverage may come close to that of the DTN nodes and reach close to 40% of the legacy nodes. Comparing this to figure 8, content availability is roughly equal for DTN and legacy nodes. Note that, the fraction of legacy nodes reached gets bigger as their number increases from L1 to L5 to L10, so the absolute number of additional nodes reached grows even more. We obtain similar findings for high (up to 40%) and low loads (up to 50%) for both text and photo applications. The SMOOTH scenario yields a qualitatively similar picture, again at much lower performance. Results of our simulations with 100 and 200 DTN nodes for all scenarios are also in line with these findings.

### 7. RELATED WORK

Our framework borrows concepts from different fields of related work to create a unique combination. Most important is the concept of embedding programs into messages and executing them in network nodes, discussed in the past as active networking [62] and
mobile code. Lee et al. [33] present a a node architecture allowing to deploy in-network services in a next generation Internet. Its main contribution is the concept of making the core network become a distributed service execution environment. It also describes an architecture for extensible router allowing for implementing new router features. Similar concepts of extensible router architecture can be also seen in works of Router Plugins [11], LARA++ [55], PromethOS [59], Pronto [21] and SARA [3]. SOFTNET [69], PLAN [23], Bowman and CANEs [36] are examples of active networking systems that assume network packets to contain programs, which are used to manage network nodes. All these systems concentrate on executing code inside the network in order to improve network capabilities, while our solution takes advantage of transformation execution to enable content access to legacy users. Moreover, active networks focus on individual (small) packets, thus limiting the amount of code that can be carried, while our message-based system is not limited by MTU size.

Baldis et al. [4] and Thorn [64] study the applicability of programming languages in mobile code. Ghezzi et al. [20] describe architectures of mobile code applications. Our framework choose one specific programming language and a specific application design tailored to the purpose of read and write access to opportunistic content messages.

Security aspects of mobile code are covered by Arden et al. [2]. He introduces a new architecture for secure mobile code that developers can use, publish and share mobile code securely across trusted domains. Older work presenting security aspects of mobile code are Rubin et al. [59], Zachary [68] and Brooks [53]. Kosta et al. [59] present the concept of using mobile code for improving code execution on mobile devices by offloading part of code execution to the cloud. Similar work by Simanta et al. [60] describes an architecture for offloading mobile code execution to hostile network environments. Unlike these works, our system uses mobile code as a tool for message content presentation and our main concern is offering an isolated execution environment for the application code so that the code does not harm the node running it (which is quite similar to the concerns of protecting routers in Active Networks).

Another set of related work concerns document presentation techniques. MINOS [9] was an early system that allowed for presentation of the multimedia content embedded in a document. Boguaraev et al. [5] presents usage of linguistic analysis tools for generation of text document description and its visualization to the user. Our framework is not limited to content presentation, but offers a full-fledged interaction to the legacy user.

Doucet et al. [16] shows an alternative approach for using native applications in the web browser by the legacy device users. This system requires web servers to have an (application-specific) gateway installed that translates a native app into a web app. On the other hand, our framework is more flexible, as it carries all transformation code inside the messages themselves so that no node requires prior knowledge of specific applications.

8. CONCLUSION

In this paper, we have presented the concept of Web Browser-based Interaction Framework that provides legacy users the ability to take part in an opportunistic network with nothing more than a standard web browser. The users can both see the content published by native applications and publish content themselves. We showed through simulations that this significantly increases the reach of the content both for legacy and native users, with overheads that do not impose a significant penalty on message delivery.

We have described our implementation of our framework for two popular opportunistic networking platforms, and enhanced a total of six applications for those platforms. This has a potential to significantly increase the attractiveness of both networks, as legacy users can access the content without having to install any extra software – a common issue for opportunistic network deployments in the real world.

There are a number of open issues to be addressed in our future work: This includes enhancing security and privacy functionality of the framework by enabling access to encrypted content for legacy users to allow the implementation of closed communication groups. One special case of closed groups will be embracing legacy users also for the point-to-point (user-to-user) unicast communication. Finally, we are exploring how to exploit web browser capabilities for establishing direct browser-to-browser communication for legacy users without a mediating entity (such as an access point).

9. REFERENCES


