Real-Time Android with RTDroid

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ABSTRACT
This paper presents RTDroid, a variant of Android that provides predictability to Android applications. Although there has been much interest in adopting Android in real-time contexts, surprisingly little work has been done to examine the suitability of Android for real-time systems. Existing work only provides solutions to traditional problems, including real-time garbage collection at the virtual machine layer and kernel-level real-time scheduling and resource management. While it is critical to address these issues, it is by no means sufficient. After all, Android is a vast system that is more than a Java virtual machine and a kernel.

Thus, this paper goes beyond existing work and examines the internals of Android. We discuss the implications and challenges of adapting Android constructs and core system services for real-time and present a solution for each. Our system is unique in that it redesigns Android’s internal components, replaces Android’s Java VM (Dalvik) with a real-time VM, and leverages off-the-shelf real-time OSes. We demonstrate the feasibility and predictability of our solution by evaluating it on three different platforms—an x86 PC, a LEON3 embedded board, and a Nexus S smartphone. The evaluation results show that our design can successfully provide predictability to Android applications, even under heavy load.

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C.3 [Special-Purpose and Application-Based Systems]: Real-time and embedded systems

General Terms
Design, Measurement, Experimentation, Performance

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Real-time Systems, Mobile Systems, Smartphones, Android

1. INTRODUCTION
There is a growing interest in adopting Android in embedded, real-time environments. A DARPA project utilizing Android is currently in development, which creates a plug and play navigation and sensor network that can scale from personal devices up to aircraft navigators [23, 24]. The UK has recently launched a satellite equipped with an Android smartphone to explore the possibility of using a smartphone as a control system [30]. In health care, much discussion is currently ongoing as to how the medical device industry can adopt Android [1, 4, 6, 7]. In these domains, the benefits are numerous; developers can leverage Android’s rich set of APIs to utilize new types of hardware such as sensors and touch screens; Android’s well-supported, open-source development environment eases application development; and many applications published in online application stores give an opportunity to incorporate creative functionalities with less effort.

However, surprisingly little work has been done in actually adding real-time capabilities in Android. The current literature only provides a short overview of potential high-level system models [21] and extensions to Android’s Java VM (Dalvik) that enable real-time garbage collection [13, 19]. The fundamental question of how to add real-time support to Android as a whole system has not been explored.

This paper presents our first step to answering that question. We analyze the real-time capabilities of Android and identify limitations. We then propose and implement redesigns of several internal components of Android to provide real-time support. We recognize, however, that Android is a vast system with many components, and that it is difficult to evaluate every aspect of Android. Thus, our goal for this paper is to identify and redesign core components central to Android, in order to support the execution of a single real-time application. As the rest of the paper shows, this goal alone has many hard challenges associated and still has broad applicability in utilizing smartphones in real-time domains such as control, medical, and military devices. It is also a prerequisite to supporting multiple real-time applications (i.e., mixed criticality [15, 17]—the ability to execute multiple components with different criticality levels safely).

More concretely, this paper makes the following four contributions. First, we analyze the real-time capabilities of Android and present the result. In addition to the kernel and JVM layers, we examine Android’s application framework, which provides programming constructs and system services to applications. We show that Android, due to its heavy reliance on unpredictable message passing mechanisms, does not provide predictable timing guarantees. We also show that system services (understandably) were not designed to support real-time.

Second, we provide an implementation that addresses the limitations discovered in our analysis. We redesign three of the core components in the application framework—a message-passing mechanism (Looper-Handler), the timer service (AlarmManager), and the sensor architecture (SensorManager)—to provide predictable
As Fig. 1a depicts, we can divide Android into roughly three layers below the application layer: (1) the application framework layer, (2) the runtime and libraries layer, and (3) the kernel layer. Android leverages a modified Linux kernel, which does not provide any real-time features such as priority-based preemption of threads, priority inversion avoidance protocols, and priority-based resource management. Previous work [13, 19] has also shown that Android’s runtime and libraries provide no real-time guarantees and Dalvik’s garbage collector can arbitrarily stall application threads regardless of priority, resulting in non-deterministic behavior. Thus, it

Figure 1: Comparison of Simplified Android and RTDroid Architectures
is currently well-understood that the bottom layers need real-time support in order to provide a predictable platform.

However, we show in this paper that even with the proper real-time features at the kernel and VM layers, Android cannot provide real-time guarantees. This is due to the fact that the application framework layer does not provide predictability for its core constructs, allowing for arbitrary priority inversion.

Broadly speaking, the application framework layer poses two problems for real-time applications, one rooted in each of its two categories shown in Fig. 1a. The first problem lies in the category shown on the right, where system services, which provide essential system services. For example, SensorManager mediates access to sensors and AlarmManager provides system timers. The issue with these system services is that the implementation of the services does not consider real-time guarantees as a requirement. In Sections 3 and 4, we discuss this problem in more detail and present our solution. Section 7 demonstrates the problem experimentally.

The second problem occurs in the category shown on the right, system services, which provide essential system services. For example, SensorManager mediates access to sensors and AlarmManager provides system timers. These components do not require a redesign and R TDroid is able to leverage them wholesale. As part of our future work, we plan to add support for hard real-time guarantees due to their use of the R TLinux kernel. Not all of the deployment profiles currently support hard real-time guarantees as a requirement. In Sections 4 and 5, we discuss this problem in more detail and present our solution. Section 7 demonstrates the problem experimentally.

The third benefit of our architecture is the streamlining of real-time application development. Developers can leverage the rich APIs and libraries that are already implemented and have support for various hardware components. Unlike other mobile OSes, Android excels in supporting a large variety of hardware with different CPUs, memory capacities, screen sizes, and sensors. Android APIs make it easier to write a single application that can run on different types of hardware. Thus, Android compatibility can reduce the complexity of real-time application development.

2.2 Overview of RTDroid

Our system, RTDroid, aims to add real-time support in Android as a whole system, thereby providing the ability to execute a single real-time application that leverages the built-in system services, such as AlarmManager and SensorManager. This necessitates that our system is predictable in time and memory usage as well as resource management. Our current system design targets a uniprocessor environment where only a single user-level process (i.e., the application process) executes. However, we believe that the design is extensible to multi-core and mixed-criticality systems. Such extensions are our future work.

2.2.1 RTDroid Architecture

In order to provide real-time support in all three layers depicted in Fig. 1a, we advocate a clean-slate redesign of Android in Fig 1b. Our redesign starts from the ground up, leveraging an established RTOS (e.g., RT Linux or RTEMS) and an RT JVM (e.g., Fiji VM). Upon this foundation we build Android compatibility. In other words, our design provides a faithful illusion to an existing Android application running on our platform that it is executing on Android. This entails providing the same set of Android APIs as well as preserving their semantics for both regular Android applications and real-time applications. For real-time applications, Android compatibility means that developers can use standard Android APIs in addition to a small number of additional APIs our platform provides to support real-time features. These additional APIs provide limited Real-Time Specification for Java (RTSJ) [14] support without scoped memory. This goal of providing Android compatibility makes our architecture unique and different from potential architectures discussed previously in the literature [? ], where much of the focus is on the kernel and the JVM layers.

2.2.2 Benefits of RTDroid

There are three major benefits of our clean-slate design. First, by using an RTOS and an RT JVM, we can rely on the sound design decisions already made and implemented to support real-time capabilities in these systems. Our RTDroid prototype uses Fiji VM [27], which is designed to support real-time Java programs from the ground up. Fiji VM already provides real-time functionality through static compiler checks, real-time garbage collection [28], synchronization, threading, etc. We note, however, that RTDroid’s design is VM independent.

The second benefit of our architecture is the flexibility of adjusting the runtime model for different use cases. This is because using an RTOS and an RT JVM provides the freedom to control the runtime model. For example, we can leverage the R TEMS [5] runtime model, where one process is compiled together with the kernel for single application deployment. With this model, an application can fully utilize all the resources of the underlying hardware. Using this runtime model is not currently possible with Android, as Android runs most system services as separate processes. Simply modifying Dalvik or the OS is not enough to augment Android’s runtime model; the framework layer itself must be changed.

The third benefit of our architecture is the streamlining of real-time application development. Developers can leverage the rich APIs and libraries that are already implemented and have support for various hardware components. Unlike other mobile OSes, Android excels in supporting a wide variety of hardware with different CPUs, memory capacities, screen sizes, and sensors. Android APIs make it easier to write a single application that can run on different types of hardware. Thus, Android compatibility can reduce the complexity of real-time application development.

2.2.3 Current Scope of Implementation

Our current RTDroid prototype redesigns three core Android components, Looper and Handler, AlarmManager and SensorManager. We have chosen these components due to their extensive use in existing Android applications as well as in our target applications. For example, Handler and Looper are essential to Android applications as they are used implicitly by every application, as we detail in Section 3. AlarmManager provides a timer service used by any application that runs periodic tasks; many real-time applications need to run periodic tasks and rely on such a service to trigger their tasks. SensorManager provides sensing APIs in Android, which are necessary for our target real-time sensing applications such as fall detectors as well as health monitors.

In addition to redesigning the above three components, we have also ported a subset of other Android programming components necessary to run an application, such as Service, Context, etc. These components do not require a redesign and RTDroid is able to leverage them wholesale. As part of our future work, we plan to increase our coverage to create a more comprehensive system.

2.2.4 Deployment Profiles

RTDroid supports three different types of deployment profiles with varying degrees of guarantees provided by the underlying platform and RTOS kernel. Not all of the deployment profiles currently support hard real-time guarantees due to their use of the RTLinux kernel and closed source drivers as we explain below.

- **Soft Real-time Smartphone**: This profile provides the lowest guarantees due to its reliance on unverified closed source
drivers and a partially preemptible RTLinux kernel as opposed to a fully preemptible RTLinux kernel. As we detail in Section 6, the Android patch to Linux is incompatible with the RTLinux patch, which prevents us from putting the kernel into a fully-preemptible mode. As such, it is only suited for soft real-time tasks. However, most applications domains, such as medical device monitoring are soft real-time systems. In this profile, task deadlines can be missed due to jitter from the kernel or blocking from the drivers. Nevertheless, we demonstrate in Section 7 that we can still provide tight latency bounds and predictability even on this profile with RTDroid.

- **Soft Real-time Desktop**: This profile provides stricter guarantees than that of the smartphone as it leverages a fully preemptible RTLinux kernel. In this profile, we can leverage verified-and-certified drivers. However, RTLinux, even in the fully preemptible kernel is not typically used in hard real-time systems. Based on current best practices, this deployment should only be used for soft real-time systems. In this profile, deadlines can be missed due to jitter from the kernel.

- **Hard Real-time Embedded**: By moving away from RTLinux and using a certified RTOS such as RTEMS as well as a development board with certified drivers for its hardware sensors, much stricter guarantees can be provided. No deadlines will be missed due to jitter from the kernel or the drivers.

### 3. RT LOOPER AND RT HANDLER

In this section as well as the next two sections, we discuss how we add real-time support in the application framework layer of Android. As discussed in Section 2, the first issue that the application framework poses lies in its message-passing constructs. These constructs do not provide any predictability or priority-awareness. We detail this issue in this section and discuss how we address it in RTDroid.

#### 3.1 Background and Challenges

Android provides a set of constructs that facilitate communication between different entities, e.g., threads and processes. There are four such constructs—Handler, Looper, Binder, and Messenger. Since any typical Android application uses these constructs, we need to support these constructs properly in a real-time context.

Among these four constructs, **Looper** and **Handler** are the most critical constructs for our target scenario of running a single real-time sensing application. This is because **Binder** and **Messenger** are inter-process communication constructs, while **Looper** and **Handler** are inter-thread communication constructs. Further, **Looper** and **Handler** are used not only explicitly by an application, but also implicitly by all applications. This is due to the fact that Android’s application container, ActivityThread, uses **Looper** and **Handler** to control the execution of an application. When an application needs to make transitions between its execution states (e.g., start, stop, resume, etc.), ActivityThread uses **Looper** and **Handler** to signal necessary actions.

**Fig. 2** shows how **Looper** and **Handler** work. **Looper** is a per-thread message loop that Android’s application framework implements. Its job is to maintain a message queue and dispatch each message to the corresponding **Handler** that can process the message. The developer of the application provides the processing logic for a message by implementing **Handler’s** `handleMessage()`. A **Handler** instance is shared between two threads to send and receive messages.

The **Looper** and **Handler** mechanism raises a question for real-time applications when there are multiple threads with different priorities sending messages simultaneously. In Android, there are two ways that **Looper** and **Handler** process messages. By default, they process messages in the order in which they were received. Additionally, a sending thread can specify a message processing time, in which case **Looper** and **Handler** will process the message at the specified time. In both cases, however, the processing of a message is done regardless of the priority of the sending thread or the receiving thread. Consider if multiple user-defined threads send messages to another thread. If a real-time (i.e., high-priority) thread sends a message through a **Looper**, its message will not be processed unless it reaches a **Handler** instance shared between two threads to send and receive messages.

![Figure 2: The Use of Looper and Handler](image)

![Figure 3: The thread in which the looper executes processes the messages sent through this handler object in the order in which they are received.](image)
processing time window for non-real-time messages, the real-time message will get delayed further by non-real-time messages.

### 3.2 Redesign

To mitigate the issues mentioned, we redesign Looper and Handler in two ways. First, we assign a priority to each message sent by a thread. We currently support two policies for priority assignment. These policies are priority inheritance, where a message inherits its sender’s priority, and priority inheritance + specified where a sender can specify the message’s priority in relation to other messages it sends.

Second, we create multiple priority queues to store incoming messages according to their priorities. We then associate one Looper and Handler for each queue to process each message according to its priority. Fig. 4 shows our new implementation for Looper and Handler. Since we now process each message according to its sender’s priority, messages sent by lower priority threads do not delay the messages sent by higher priority threads. For memory predictability, queues can be statically configured in size.

### 3.3 Worst-Case Execution Time

We now formally show how our new design provides predictability. The worst-case execution time is the best metric for this purpose as it gives the upper bound on execution time. To understand the worst-case execution characteristics of the Real-time Looper and Handler, we need to reason how the constructs process a series of messages and execute each message’s callback function. We define $T^i_j$ to be the $i^{th}$ message issued by the application from a thread with priority $j$. The messages are passed into a real-time Looper that has the same priority as the messages and then they are enqueued in a MessageQueue. The time cost for handling the $i^{th}$ message in priority level $j$ is shown as $S^i_j$ in Equation (1): \[ S^i_j = \sum_{l=0}^{j} (h^i_l + deq(T^i_j)), \] (1) Where $h^i_j$ is the cost of time to handle $T^i_j$ and $deq(T^i_j)$ is the cost of dequeuing from the message queue.

To reason about the worst-case execution time for a message $m$, we must first calculate the processing time for all messages that have priorities greater than or equal to the priority of message $m$, shown in Equation (2): \[ phase_0(T^i_j) = \sum_{p > j} S^p_{\text{last}} + S^i_j. \] (2) Where last is the last message in the message queue with priority $p$ that is greater than $j$. Since the system also handles new incoming messages, which may have a priority greater than or equal 3 to that of $m$, we must also define the system in terms of a message arrival rate $R$ for a given priority $p$.

We divide the amount of time for the system to handle $m$ into a number of phases. During the phase $n$, the system handles all of the messages in the priority queue which are greater than or equal to the priority of $m$ as shown in Equation 2. While handling the message in the current phase, new messages arrive at a given rate per priority level, the system must then handle each of the new messages with priority greater than or equal to $m$ before handling message $m$.

In order to quantify the number of messages in each priority queue, we define a sending rate for each group of clients with priority $p$, $R_p$. When $n \geq 1$, the worst-case handling time is integrating all of the handling times for messages that are greater than or equal to the priority of message $m$, as shown in Equation (3): \[ phase_n(T^i_j) = \sum_{p \geq j} \sum_{i=0}^{\text{last}} (h^i_l + deq(T^i_j) + enq(T^i_j)). \] (3) Where enq($T^i_j$) is the cost of enqueuing in the message queue.

The LHS represents the upper bound of the time cost for message handling for phase $n$, the RHS represents the total time cost for handling all messages that arrive during phase $n-1$. The outer summation is the time to handle each priority level and the inner summation is the integration of the time to handle all of the same priority messages that have arrived in the phase $n-1$. phase$_{n-1}(T^i_j)$ represents the time spent in previous phase, and when multiplied by the rate $R_p$ gives the number of messages currently in each priority-based queue. The recursion ends when phase$_n$ is smaller than the unit of time. Thus, the summation of all phases is the actual worst-case execution time for handling message $m$ as shown in Equation (4): \[ WCET(T^i_j) = \text{phase}_{n-1}(T^i_j) + \text{phase}_1(T^i_j) + \cdots + \text{phase}_{n-1}(T^i_j) + \text{phase}_n(T^i_j). \] (4)

Notice, the system is only well defined (i.e., able to process messages with real-time guarantees) if the worst-case execution time for each message is less than the deadline for processing that message relative to its arrival time and if phase$_n$ is less than phase$_{n-1}$.

### 4. RT ALARM MANAGER

As mentioned in Section 2, the second issue that Android’s application framework layer poses for real-time support is that system services do not provide real-time guarantees. Since Android mediates all access to its core system functionalities through a set of system services, it is critical to provide real-time guarantees in the system services. Just to name a few, these services include SensorManager that mediates all sensor access and data acquisition; and AlarmManager that provides a timer service.

The presence of these system services raises two questions. First, in our target scenario of running a single real-time application, there is no need to run system services as separate processes; rather it is more favorable to run the application and the system services as a single process to improve the overall efficiency of the system. Then the question is how to redesign the system service architecture in our platform in order to avoid creating separate processes.

3 Although our Looper and Handler uses a FIFO priority queue, we are abstracting the complexities of the data-structure algorithm, such as queuing and dequeuing costs, in the calculation and thus creating a generalized equation applicable to all our RT redesigns.
while preserving the underlying behavior of Android. Second, as we show in this section and the next section, the internals of these system services do not consider real-time support as a design requirement.

To answer these two questions, we redesign two of the system services—AlarmManager and SensorManager. In this section we first show how we redesign AlarmManager to provide real-time guarantees. In the next section, we discuss our SensorManager redesign.

4.1 Background and Challenges

AlarmManager receives timer registration requests from applications and sends “timer triggered” messages to these applications when its timer fires. Since real-time applications frequently rely on periodic and sporadic tasks, it is important to provide real-time guarantees in AlarmManager.

Fig. 5 shows how AlarmManager works, including alarm registration and alarm delivery. An IPC call, with a message and its execution time, is made to the AlarmManager every time an application registers an alarm. When the alarm triggers at the specified time, the AlarmManager sends a message back to the application, and the associated callback is executed. The issue with AlarmManager is that it provides no guarantee on when or in what order alarm messages are delivered, hence does not provide any timing guarantee or priority-awareness.

4.2 Redesign

We redesign both alarm registration and delivery mechanisms to support predictable alarm delivery. For alarm registration, we use red-black trees to maintain alarms as shown in Fig. 6. This means that we can make the registration process predictable based on the complexity of red-black tree operations, i.e., the longest path of a tree is no longer than twice the shortest path of the tree. We use one red-black tree for storing timestamps and pointers to per-timestamp red-black trees. Per-timestamp trees are leveraged to order alarms based on the same sender’s priority. Thus, our alarm registration process is essentially one insertion operation to the timestamp tree and another insertion operation to a per-timestamp tree. By organizing the alarms based on senders’ priorities, we guarantee that an alarm message for a low priority thread does not delay an alarm message for a high priority thread. Expired alarms are discarded. Note that this ensures that low priority threads whose alarm registration rate exceeds the alarm delivery capacity of the system cannot prevent a high priority alarm from being triggered.

For alarm delivery, we create an AlarmManager thread and assign the highest priority for timely delivery of alarm messages. This thread replaces the original multi-process message passing architecture of Android. It wakes up whenever an application inserts a new alarm into our red-black trees, then it schedules a new thread at the specified time for the alarm. We associate the application’s callback for the alarm message with this new thread. For precise execution timing of this callback thread, we implement Asynchronous Event Handlers (AEH) that Real-Time Specification for Java (RTSJ) [14] specifies the interface for.

We have implemented two versions for AEH. The first is a per-thread AEH implementation used in our workshop paper [32], which creates one thread per handler to process a given event type. This simple mechanism is efficient in handling low numbers of events, but can create memory and processing pressure due to large number of handling threads if a large number of events occur within the same time period. Although most Android applications do not register alarms at a frequency that would cause problems, our system must be resilient to such behavior nonetheless.

The second mechanism leverages a thread pool with a statically configured number of threads, which reduces the number of threads that we need to create. Our implementation is based on Kim et al.’s proposed model [20] and is similar to how the jRate [10] implements RTSJ’s AEH. The benefit of this implementation is a hard, statically known limit on the number of threads to handle asynchronous events. There is lower memory usage due to less threads being created and the output is deterministic with a well-known, predictable behavior [10].

4.3 Worst-Case Execution Time

The worst-case execution scenario for AlarmManager is similar to that discussed for the Looper and Handler in Section 3.3. The upper bound of delivery and execution of an alarm consists of 1) the delivery and execution of all alarms that have been registered with priority greater or equal to that of a, 2) the delivery and execution of all newly registered alarms with priority greater or equal to a based on a per priority rate of alarm delivery and registration. The equation of WCET for AlarmManager is the same pattern as shown in Equation (1), (2), (3), (4), but couched in terms of alarm processing instead of message delivery.

- $T_i^j$ represents the $i^{th}$ alarm registered by application with priority $j$.
- $S_i^j$ represents the time cost for handling the $i^{th}$ alarm in priority level $j$.
5. *RT SENSOR ARCHITECTURE*

Another system service we redesign in RTDroid is **SensorManager**. Modern mobile devices are equipped with many sensors such as accelerometers, gyroscopes, etc. Android, mainly through its **SensorManager**, provides a set of APIs to acquire sensor data. This section examines the current sensor architecture of Android and presents our new design for real-time support.

### 5.1 Background and Challenges

On Android, sensors are broadly classified into two categories. The first category is **hardware** sensors, which are the sensors that have a corresponding hardware device. For example, accelerometer and gyroscopes belong to this category. The second category is **software** sensors, which are “virtual” sensors that exist purely in software. Android fuses different hardware sensor events to provide software sensor events. For example, Android provides an orientation sensor in software. On Nexus S, Android 4.2 has 6 hardware sensors and 7 software sensors. These sensors are available to applications through **SensorManager**. An application registers sensor event listeners through the provided APIs. These listeners provide the application’s callbacks that Android framework calls whenever there is any requested sensor event available. When registering a listener, an application can also specify its desired delivery rate. The Android framework uses this as a hint when delivering sensor events.

Internally, there are four layers involved in the overall sensor architecture—the kernel, HAL, **SensorService**, and **SensorManager**. Fig. 7 shows a simplified architecture.

1. **Kernel**: The main job of the kernel layer is to pull hardware sensor events and populate the Linux /dev file system to make the events accessible from the user space. Each sensor hooks to the circuit board through an I²C bus and registers itself as an *input device*.

2. **HAL**: The HAL layer provides sensor hardware abstractions by defining a common interface for each hardware sensor type. Hardware vendors provide actual implementations underneath.

3. **SensorService**: **SensorService** converts raw sensor data to more meaningful data using application-friendly data structures. This involves three steps. First, **SensorService** polls the Linux /dev file system to read raw sensor input events. Second, it composites both hardware and software sensor events from the raw sensor input events. For hardware sensors, it just reformats the data; for software sensors, it combines different sources to calculate software sensor events via sensor fusion. Finally, it writes each sensor event to the **SensorEventQueue** via **SensorEventConnection**.

4. **Framework Layer**: **SensorManager** delivers the sensor events by reading the data from **SensorEventQueue** and invoking the registered application listeners to deliver sensor events.

There are two issues that the current architecture has in providing predictable sensing. First, there is no priority support in the sensor event delivery mechanism since all sensor events go through the same **SensorEventQueue**. When there are multiple threads with different priorities, the event delivery of lower-priority threads can delay the event delivery of higher-priority threads. Second, the primary event delivery mechanisms poll and buffer at the boundary of different layers (e.g., between the kernel and **SensorService** and between **SensorService** and **SensorManager**) by use of message passing constructs. Android does not provide any guarantee on how long it takes to deliver events through these mechanisms.

### 5.2 Redesign

We redesign the sensor architecture for RTDroid to address the two issues mentioned above. Our design is inspired by event pro-
ority inheritance has two implications. First, when an application sign the highest priority available in the system to the polling thread also inherits the original priority thread that executes a sensor event listener callback, this new thread in addition, when the delivery thread creates a new processing thread inherits the priority of the highest-priority appli-
tions. When an application thread of priority through our priority inheritance mechanism described next. We address the two issues mentioned earlier by priority inheri-
tions, one thread for a hardware sensor reformats raw sensor data for each sensor type. For ex-
amples, a processing thread for a hardwared sensor reforms raw sensor data using an application-friendly format, and a processing thread for a software sensor performs sensor fusion. Once the raw sensor data is properly processed, each processing thread notifies the delivery thread whose job is to create a new thread that executes the sensor event listener callback registered by an application thread. To provide predictable delivery, we use notification, not polling, for our event delivery except in the boundary between the kernel and the polling thread. We provide additional predictability through our priority inheritance mechanism described next.

We address the two issues mentioned earlier by priority inheritance. When an application thread of priority \( p \) registers a listener for a sensor, say, gyroscope, then the processing thread for gyroscope inherits the same priority \( p \). If there are multiple application threads that register for the same gyroscope, then the gyroscope processing thread inherits the priority of the highest-priority application thread. In addition, when the delivery thread creates a new thread that executes a sensor event listener callback, this new thread also inherits the original priority \( p \) of the application thread. We assign the highest priority available in the system to the polling thread to ensure precise timing for data pulling.

This combined use of event-based processing threads and priority inheritance has two implications. First, when an application thread registers a listener for a sensor, we effectively create a new, isolated event delivery path from the polling thread to the listener. Second, this newly created path inherits the priority of the original application thread. This means that we assign the priority of the application thread to the whole event delivery path.

5.3 Worst-Case Execution Time

The worst-case execution scenario for \( \text{SensorManager} \) is slightly different than what we have discussed in Section 3.3 and 4.3. The upper bound for delivery of the sensor event to a sensor listener, \( l \), consists of three parts: (1) the time cost of the system delivery the sensor event to all sensor listeners that registered a listener that are greater or equal to the priority of \( l \), (2) recursively integrate the time cost for register and deliver of the sensor data for the new higher-priority listener arriving at a per priority rate, and (3) the time cost for polling the data from each sensor kernel module. The WCET equation for \( \text{SensorManager} \) is in the same fashion as previously defined in Equation (1), (2), (3), and (4), and includes the sensor data polling cost as shown in in Equation. 5, 6:

\[
\text{phase}_0(T_i^j) = \sum_{p \geq j} P_j(\text{sensor}_c) + \sum_{p \geq j} S_{\text{last}}^j + S_i^j
\]

\[
\text{phase}_n(T_i^j) = \sum_{p \geq j} \sum_{i=0}^{\text{phase}_{n-1}(T_i^j)} R_p (h_i^j + \text{deq}(T_i^j) + \text{enq}(T_i^j)).
\]

- \( T_i^j \) represents the \( i \)th sensor listener in application with priority \( j \).
- \( S_i^j \) represent the time cost to execute the \( i \)th callback of sensor listener in priority level \( j \).
- \( h_i^j \) is the amount of time to execute the callback of sensor listener of \( T_i^j \).
- \( \text{deq}(T_i^j) \) is the cost of listener registration.
- \( \text{last} \) is the sensor listener in priority \( p \) that is greater than \( j \).
- \( P_j(\text{sensor}_c) \) is the cost of sensor data polling.

6. REAL-TIME BUILDING BLOCKS

In this section, we report our experience in replacing non-real-time building blocks (Dalvik and Linux) with off-the-shelf real-time counterparts (Fiji VM and RTOs). As mentioned earlier, we support three deployment profiles, an x86 PC environment, an embedded environment with a LEON3 development board, and an ARM-based smartphone environment with a Nexus S smartphone. The x86 and the LEON3 environments do not require any more than replacing the non-real-time kernel with either real-time Linux kernel (by applying an RT-Preempt patch, i.e., RTLinux) or the real-time RTOS kernel. The same strategy, however, does not work for the smartphone environment because Android has introduced extensive changes in the kernel that are not compati-
ble with R TLinux patches. Thus, we first briefly describe our x86 and LEON3 environments. We then report our experience with the smartphone environment in detail.

6.1 x86 PC and LEON3

For the x86 environment, we apply an RTLinux patch (patch-3.4.45-rt60) to Linux 3.4.45, and use Fiji as the real-time VM. Fiji already runs on RTLinux, thus it did not require any additional ef-
fort. This configuration represents our soft real-time deployment. Tighter bounds are provided as RTLinux makes the kernel fully preemptible. Similarly, we can introspect the drivers on the ma-
chance to guarantee their timeliness or leverage off-the-shelf drivers that have already been vetted.

To create the LEON3 environment, we use a LEON3 embedded board, GR-XC65-LX75, manufactured by GaIsler. We then use RTiEMS as the real-time kernel and Fiji as the real-time VM. RTiEMS has native support for LEON3 and Fiji already supports RTiEMS. This configuration represents our hard real-time embedded board deployment, avoiding the issues that plague RTiLinux and closed source drivers. The LEON3 manufacturers provide drivers that have previously been certified for automotive, aerospace, and civilian aviation.

In order to test the SensorManager on the LEON3 system, we have designed and implemented an accelerometer daughter board as well as the associated RTiEMS compliant driver.

6.2 Nexus S Smartphone

Unfortunately, the same approach is not adequate for executing real-time applications on an Android phone. This is mainly due to the incompatibilities between Android and the real-time building blocks in the kernel layer as well as in Android’s C library, Bionic. The following are the main challenges to integration.

6.2.1 Bionic

Android does not utilize glibc as the core C library, instead it uses its own library called Bionic [12]. Bionic is a significantly simplified, optimized, light-weight C library specifically design for resource constrained devices with low frequency CPUs and limited main memory. Its architectural targets are only ARM and x86.

Bionic becomes a problem when replacing Dalvik with Fiji; this is because it does not support the real-time extensions for Pthreads and mutexes, which are required by Fiji (or any other real-time Java VM). In addition, it is not POSIX-compliant. Thus, we have modified Bionic to include all necessary POSIX compliant real-time interfaces. This includes all the real-time extensions for Pthreads and mutexes.

6.2.2 Incompatible Kernel Patches

Android has introduced a significant amount of changes specializing the Linux kernel for Android, e.g., low memory killer, wake-lock, binder, logger, etc. Due to these changes, automatic patching of an Android kernel with an RTiLinux patch is not possible, requiring a manually applied RTiLinux patch.

Even after manual patching, however, we have discovered that we are still not able to get a fully-preemptible kernel which can provide tighter latency bounds. The reason is simply that Android’s changes are not designed with full preemption in mind. We are currently investigating this issue and it is likely that this is an engineering task. Nevertheless, we are not aware of any report of a fully-preemptible Android kernel.

6.2.3 Non-Real-Time Kernel Features

During our initial testing and experimentation, we have discovered that there are two kernel features that are not real-time friendly. They are the out of memory killer (OOM killer) [2] and CPUFreq governor [11]. The OOM killer is triggered when there is not enough space for memory allocation. It scans all pages for each process to verify if the system is truly out of memory. It then selects one process and kills it. We have found out that this causes other threads and processes to stop for an arbitrary long time, creating unpredictable spikes in latency. For our target scenario of running a single real-time application, the OOM killer is not only unnecessary, but a source of missed real-time task deadlines. Memory management is provided by Fiji VM’s Schism, which is a real-time, fragmentation tolerant GC [28]. It is therefore, critical to disable OOM killer.

CPUFreq governors offer dynamic CPU frequency scaling by changing the frequency scaling policies. Android uses this to balance between phone performance and battery usage. The problem is that when a CPUFreq governor changes the frequency, it affects the execution time of all running threads, again introducing jitter in the system. Moreover, frequency scaling is not taken into consideration when scheduling threads. The result is missed task deadlines and unpredictable spikes in latency. Although not the focus of our experiments, we note that real-time scheduling that takes voltage scaling into consideration has been vetted for hardware architectures with specialized mechanisms for predictability [9].

In our experiments, we show the behavior of RTDroid with two governors—the “ondemand” governor, which dynamically changes the CPU frequency depending on the current usage, and the “performance” governor, which sets the CPU frequency to the highest frequency possible. We leave it as our future work to handle dynamic frequency scaling. For example, we can apply an existing method for worse case execution time analysis [22] to validate the hardware and leverage this timing analysis to modify the kernel and VM schedulers appropriately.

7. EXPERIMENTAL RESULTS

To measure and validate our prototype of RTDroid, we tested our implementation on three system level configurations, each of which represents one of our target deployments discussed in Section 2.2.4. The first configuration utilizes an Intel Core 2 Duo 1.86 GHz Processor with 2GB of RAM. For precise timing measurements, we disabled one of the cores prior to running the experiments. The second configuration is a Nexus S phone equipped with a 1 GHz Cortex-A8 and 512 MB RAM along with 16GB of internal storage and an accelerometer, gyro, proximity, and compass sensors running Android OS v4.1.2 (Jelly Bean) patched with RT Linux v.3.0.50. For the third configuration we leveraged a GR-XC65-LX75 LEON3 development board running RTiEMS version 4.9.6. The board’s Xilinx Spartan 6 Family FPGA was flashed with a modified LEON3\(^3\) configuration running at 50Mhz. The development board has an 8MB flash PROM and 128MB of PC133 SDRAM. We present observed, end-to-end worst-case execution times as it is difficult to provide the latency breakdown for the whole system without specialized timing hardware. We therefore focus on showing the timeliness of our system on a series of stress tests. We couple the worst observed latency/processing time for each experiment with the algorithmic characterization of each component, individually presented in Sections 3.3, 4.3, and 5.3.

We have designed and developed a daughter board with interface circuitry based on an MMA8452Q triple axis accelerometer. We have developed an RTiEMS driver for the accelerometer and integrated it into our RTiEMS build.

Due to space constraints, we only show a subset of our experimental results. All of our results are available through our website: http://rtroid.cs.buffalo.edu.

7.1 RT Looper and RT Handler

To measure the effectiveness of our prototype, we have constructed an experiment that leveraged RT Looper and RT Handler. Our microbenchmark creates one real-time task with a 100 ms period that sends a high-priority message. To measure the predictability of the system, we calculate the latency of processing the

\(^3\)The LEON3 core was reconfigured to allow access to a specific I^2C bus so that the accelerometer could be connected to the board.
message, determined by two timestamps. The first timestamp is taken in the real-time thread prior to sending the message. This timestamp is the data encoded within the message. The second timestamp is taken within the RT Handler responsible for processing this message after the message has been received and the appropriate callback invoked. The difference between these two timestamps is the message’s latency.

In addition, the experiments include a number of low-priority threads which also leverage RT Looper and RT Handler. These threads have a period of 10 ms and send 10 messages during each period. To compare the Looper and Handler designs between RTDroid and Android, we have ported the relevant portion of Android’s application framework, including Looper and Handler, so we can compile and run our benchmark application on x86. Thus, on Android, all threads, regardless of their priorities, use the same Looper and Handler—this is the default behavior. On RTDroid, each thread uses a different pair of RT Looper and RT Handler according to its priority—this is opaque to the application developer and handled automatically by the system.

To measure the predictability of our constructs under a loaded system, we increase the number of low-priority threads. We have executed each experiment for 40 seconds, corresponding to 400 releases of the high-priority message, and have a hard stop at 50 seconds. We measure latency only for the high-priority messages and scale the number of low-priority threads up to the point where the total number of messages sent by the low-priority threads exceeds the ability to process those messages within the 40 second execution window. On both Intel Core 2 Duo and Nexus S, we have varied the number of low-priority threads in increments of 10 from 0-300. Considering memory and other limitations of our resource constrained embedded board, we have run the experiments increasing the low priority threads in increments of 5 from 5-30 when running on the LEON3 board.

Fig. 9 and Fig. 10 demonstrates the consistent latency of our RT Looper and RT Handler implementation. On the desktop, we observe most of the latency for messaging is between 22 µs and 50 µs with any number of threads, and the variance is around 20 µs from the lowest to the highest latency in any given run. The worst observed latency variance is 26 µs. This degree of variance on the system is attributed to context switch costs and scheduling queue contention. On the LEON3 development board, the result shows a similar pattern. In contrast, the huge variance of Android on both platforms clearly indicate its inability to provide real-time guarantees.

Fig. 11 shows the results on Nexus S. We run two series of experiments, one with the ondemand governor and the other one with the performance governor. It was observed that the latency of the tests with the ondemand governor decreases with an increasing number of threads, while the performance governor maintains a relatively consistent latency.
of low-priority threads. This is due to the extra load on the system, which results in the CPU’s frequency being increased by the on-demand governor. The tests with the performance governor show a consistent latency in any given run, since the CPU frequency does not change. On the other hand, the latency variation from Android is several orders of magnitude greater than that of RTDroid as shown in Fig. 11a.

7.2 RT AlarmManager

Measuring the performance of the RT AlarmManager was done with an experiment consisting of scheduling of a single high-priority alarm at the current system time + 40 ms, while increasing the number of low-priority alarms scheduled at the exact same time. We measure two types of latency for the experiment: 1) the entire latency of the alarm delivery (Delivery latency), which is the difference between the scheduled time and actual execution time of the high-priority alarm, and 2) the latency of the asynchronous event fire (AEEvent fire latency), which is the difference between the scheduled time and the actual firing time by the AlarmManager. The difference between the two types of latency shows how long it takes for the system to deliver an alarm from the AlarmManager to the application. We run the experiment on all three platforms. These results show the timing and latency of the alarm execution process and indicate that the RT AlarmManager is efficient at prioritizing high-priority alarms and scheduling them at their specified time.

As mentioned in Section 4, we have implemented two techniques for alarm management in RT AlarmManager—one with a per-thread AEH implementation used in our previous workshop paper [32] and another implemented with a thread pool. We show the predictability of RTDroid with each technique by using threads ranging from 5-100 and a thread granularity of 10. To induce queueing in the thread pool implementation, only 3 worker threads are allocated for the thread pool.

7.2.1 x86 Desktop

Fig. 12 shows the results of the per-thread AEH and the thread pool AEH experiments running on RTLinux. The latency of the entire alarm delivery for per-thread AEH on the x86 is bounded from 220 µs to 331 µs with a 32 µs standard deviation. The Asynchronous event fire latency is consistently around 105 µs. The thread pool implementation exhibits a slightly slower performance with the alarm delivery bounded from 255 µs to 355 µs with a 29 µs standard deviation. This small performance drop is expected and caused by alarm queuing in the thread pool itself.

7.2.2 Nexus S Smartphone

Fig. 13 demonstrates the results with the same experimental scenario on the Nexus S smartphone. It shows the same pattern as the x86 does, but with a larger value. This is not surprising considering the hardware difference between X86 and smartphone in terms of the type and frequency of their CPU and available memory. On av-
eration, the thread pool shows less than 1 ms latency and the worst observed case is 1.2 ms for both of the per-thread AEH and thread pool implementations, with 108 µs and 92 µs deviation.

7.2.3 LEON3 Embedded Board

We have conducted a similar set of experiments on LEON3. Our results, however, show little difference from our x86 and Nexus S results. Due to this reason and space considerations, we do not include the graphs. Overall, for both AEH implementations across platforms, our experiments show that high-priority threads execute in a deterministic fashion and with tight bounds. This is irrespective of the number of low-priority threads that exist in the system.

7.3 Real-Time Fall Detector

To validate the predictability of our sensor architecture in data delivery, we have created a soft real-time fall detection application that leverages our SensorManager outlined in Section 5. We designed two experiments with two different types of workloads: (1) a memory intensive load and (2) a computation intensive load. The memory intensive experiment creates a varying number of non-real-time priority threads that each allocate a 2.5 MB integer array storing integer objects. The thread then assigns every other entry in the array to null. The effect of this operation is to fragment memory. The thread then assigns every other entry in the array to null. The effect of this operation is to fragment memory.

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7.3.1 Nexus S Smartphone

Fig. 14 illustrates the observed latency of the sensor event delivery for the fall detection application. To stress the predictability of our SensorManager implementation, we have injected memory and computationally intensive threads into the application itself that run alongside of the fall detecting thread. We set these additional threads to a low priority. The Fig. 14a, Fig. 14b, Fig. 14d, and Fig. 14e show the latency of sensor event delivery with one low-priority thread and 100 low priority threads. The upper bound of these four runs was always around 30 ms, and there is no perceivable difference between executing the application with or without memory and computationally intensive threads. For comparison we provide Android performance numbers in Fig. 14c and Fig. 14f to show the effect of low-priority threads on sensor event delivery in stock Android.

7.3.2 LEON3

Fig. 15 lists the results of running the system unloaded, with 30 computational threads and with 30 memory intensive threads. The typical latency is 5.5 ms with a very low standard deviation. The memory intensive test shows a greater variability in the sensor event delivery times but they still fall under 6.5 ms and are also typically 5.5 ms also. RTDroid deployed on this platform creates a very stable system, especially when compared to the results of stock Android.
both Android and RTDroid running on the Nexus S as is shown in Fig. 14.

8. RELATED WORK

Recent work has performed preliminary studies on the real-time capabilities of Android. Maia et al. evaluated Android for real-time and proposed the initial models for a high-level architecture [21]. The study did not explore the Android framework, services, IPC, nor core library implementations for their suitability in a real-time context. We believe our work further refines the proposed models.

The overall performance and predictability of DVM in a real-time setting was first characterized by Oh et al. [25]. Their findings mirror our general observations on Android. In general, Android performs well in many operational conditions. However, the core system does not provide any guarantees, and the worst-case execution time is parameterized by other applications and components in the system. Thus, to provide real-time guarantees, we need to alter the core system constructs, the libraries, and system services built from them.

Kalkov et al. [19] outline how to extend DVM to support real-time; they observed that DVM’s garbage collection mechanism suspends all threads until it finishes garbage collection. This design is obviously problematic for applications that need predictability. The suggested solution is to introduce new APIs that allow developers to free objects explicitly. While this design decision does not require a redesign of the whole Dalvik GC, relying on developers to achieve predictability adds a layer of complexity. In addition, their work does not explore how different components within a single application (or across multiple applications) interact through Android’s core constructs. We have observed that the structure of many of Android’s core mechanisms, from which many services and libraries are constructed, need to be augmented to provide real-time guarantees. Thus, we believe our implementation is synergistic to such proposals and can be leveraged to provide predictability when applications leverage services, IPC, or the core Android constructs.

9. CONCLUSIONS AND FUTURE WORK

This paper has presented RTDroid, a variation of Android that aims to provide real-time capabilities to Android as a whole system. We have shown that replacing DVM with an RT JVM and Linux with an RTOS is insufficient to run an Android application with real-time guarantees. To address this shortcoming, we have redesigned Android’s core constructs and system services to provide tight latency bounds to real-time applications. Our experiments with three platforms—an x86 PC, a LEON3 embedded board, and a Nexus S smartphone, show that RTDroid has good observed predictability on several microbenchmarks as well as a real-time application across three distinct deployment profiles.

Our future work includes the development of Android specific real-time APIs and the design of new programming constructs that naturally support real-time applications on RTDroid. We also plan to extend the current Android’s application manifest in order to enable the static definition of real-time features. In parallel, we are working on supporting multi-application execution using Fiji’s mixed-criticality support [8, 33] and just-in-time compilation of real-time applications.

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