Experimental Bring-Up and Device Driver Development for BeagleBone Black: Focusing on Real-Time Clock Subsystems

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***Abstract*—This paper presents a detailed experimental study on the board bring-up and device driver development process for the BeagleBone Black, with a specific focus on real-time clock (RTC) subsystems. The work is motivated by the increasing demand for precise and persistent timekeeping in embedded systems used in industrial automation, IoT deployments, and real-time applications. Given the critical role of RTCs in maintaining time during power cycles or system restarts, ensuring their reliable integration at the kernel level is essential. The study begins with the hardware initialization sequence, covering the bootloader configuration, device tree customization, and verification of peripheral interfaces. This foundational process ensures a stable Linux environment capable of supporting custom hardware drivers.**

The second phase of the work concentrates on the development and deployment of an RTC driver within the Linux kernel framework. Both internal and I2C-based external RTCs are explored, with the design addressing device registration, time reading and writing routines, and integration with user-space utilities. The implemented driver demonstrates accurate timekeeping and seamless hardware communication, verified through diagnostic tools and runtime behavior. The results not only validate the effectiveness of the RTC subsystem integration but also highlight the adaptability of BeagleBone Black as a reliable platform for embedded system prototyping and research. This work serves as a practical guide for developers involved in low-level system design and peripheral interfacing on ARM-based platforms.

***Keywords*—BeagleBone Black, Board Bring-Up, Real-Time Clock (RTC), Embedded Linux, Device Driver Development, Kernel Module**

I. INTRODUCTION

Embedded systems have become integral to various applications, ranging from industrial automation to consumer electronics. These systems often require precise timekeeping, efficient power management, and reliable hardware-software integration. The BeagleBone Black (BBB), a low-cost, community-supported development platform based on the AM335x ARM Cortex-A8 processor, offers a robust environment for developing and prototyping embedded applications [4].

A critical phase in embedded system development is the board bring-up process, which involves initializing and validating hardware components, bootloaders, and operating systems. This process ensures that the hardware functions as intended and lays the groundwork for subsequent software development [2]. Figure 1 illustrates the typical stages involved in the board bring-up process.

An essential component in many embedded systems is the Real-Time Clock (RTC), which maintains accurate timekeeping even when the main system is powered off. RTCs are crucial for scheduling tasks, logging events, and ensuring time synchronization across systems [3]. The integration of RTCs into embedded platforms like the BBB enhances their applicability in time-sensitive applications.

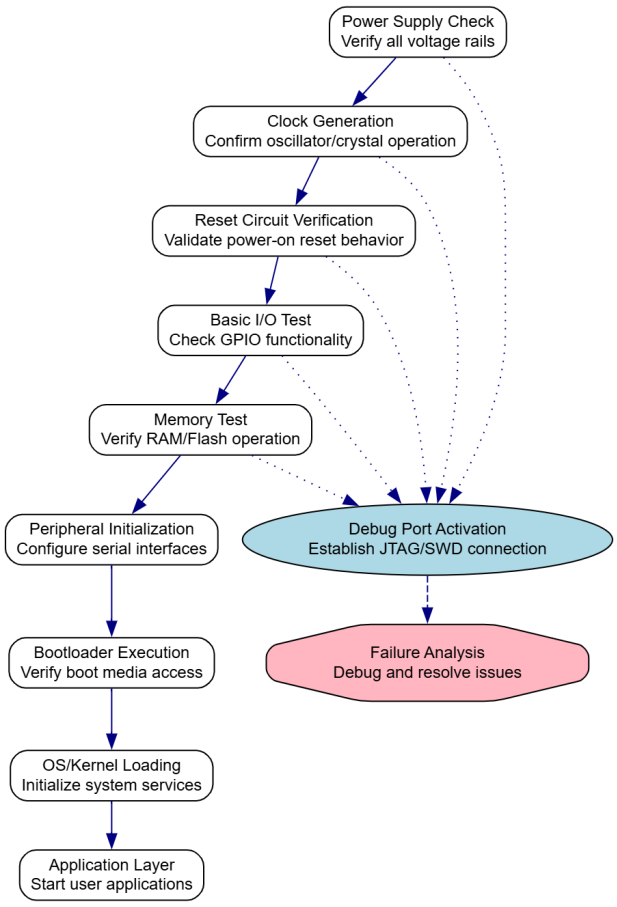

Fig. 1. Typical Board Bring-Up Process Flow

The primary objectives of this research are:

- To perform a comprehensive board bring-up of the BeagleBone Black, ensuring all hardware components and interfaces are correctly initialized.
- To develop and integrate a custom RTC driver within the Linux kernel, facilitating accurate timekeeping functionalities.
- To evaluate the performance and reliability of the imple-

mented RTC subsystem in various operational scenarios.

Table I summarizes the key features of the BeagleBone Black relevant to this study.

TABLE I
BEAGLEBONE BLACK KEY FEATURES

Feature	Description
Processor	AM335x 1GHz ARM Cortex-A8
Memory	512MB DDR3 RAM
Storage	4GB 8-bit eMMC on-board flash
Connectivity	USB, Ethernet, HDMI
Expansion	2x46 pin headers
Operating System	Debian Linux

The contributions of this paper are twofold: first, it provides a detailed methodology for bringing up the BBB platform, addressing common challenges and solutions; second, it presents the development and integration of a custom RTC driver, enhancing the system's capability for accurate timekeeping. This work aims to serve as a reference for developers and researchers involved in embedded system design and development.

II. BACKGROUND AND RELATED WORK

A. AM335x SoC and BeagleBone Black Architecture Overview

The BeagleBone Black (BBB) is a low-cost, community-supported development platform built around the Texas Instruments Sitara AM335x System-on-Chip (SoC), which features a 1 GHz ARM Cortex-A8 processor [4]. The AM335x SoC integrates various peripherals, including memory interfaces, timers, and communication protocols, making it suitable for embedded applications.

B. Linux Kernel Device Driver Model

The Linux kernel employs a unified device driver model that abstracts hardware details and provides a standardized interface for driver development. This model organizes devices and drivers into a hierarchical structure using core data structures like `struct device`, `struct device_driver`, and `struct bus_type` [5]. This abstraction facilitates modularity and scalability in driver development.

C. Existing RTC Subsystems in Embedded Linux

Real-Time Clocks (RTCs) are essential for maintaining accurate timekeeping in embedded systems. The Linux kernel's RTC subsystem provides a standardized interface for RTC devices, supporting features like time read/write, alarms, and interrupts [6]. The subsystem includes drivers for various RTC chips, such as the DS1307 and DS3231, which communicate over interfaces like I2C.

D. Survey of Similar Development Efforts

Several development efforts have focused on integrating RTC modules with the BeagleBone Black. For instance, the DS3231 RTC module has been successfully interfaced using I2C, with device tree overlays facilitating its integration [7]. Additionally, tutorials and community forums provide guidance on wiring and configuring external RTCs with the BBB [8].

AM335x SoC Block Diagram (TI Sitara Processor)

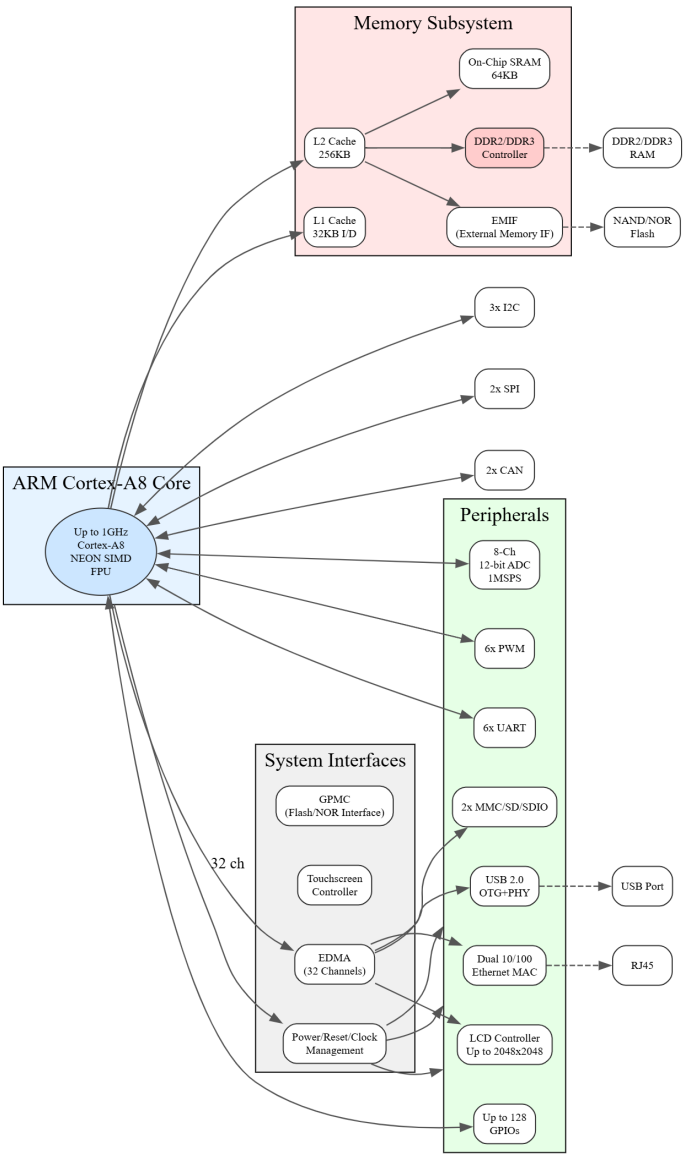

Fig. 2. AM335x SoC Block Diagram

III. BEAGLEBONE BLACK BOARD BRING-UP

A. Hardware Setup and Configuration

The initial phase of the BeagleBone Black (BBB) board bring-up involves establishing a reliable hardware setup. The BBB can be powered via a 5V DC barrel jack or through the USB interface. For development purposes, USB power is often preferred due to its dual role in providing power and facilitating serial communication. A micro-USB cable connects the BBB to a host computer, enabling access to the serial console and network interfaces. Additionally, a microSD card is prepared with the desired bootloader and operating system images, serving as the primary storage medium during the bring-up process.

B. Boot Process: ROM Code → SPL → U-Boot → Kernel

The boot sequence of the BBB is a multi-stage process. Upon power-up, the on-chip ROM code executes, scanning predefined boot sources based on the SYSBOOT pin configuration. If a valid bootloader is found on the microSD card or eMMC, the ROM code loads the Secondary Program Loader (SPL), also known as MLO. The SPL initializes essential hardware components and subsequently loads the U-Boot bootloader. U-Boot is responsible for loading the Linux kernel and the device tree blob (DTB) into memory, eventually transferring control to the kernel to commence system operation.

C. Device Tree and Peripheral Initialization

The Linux kernel utilizes the Device Tree (DT) mechanism to abstract hardware details, facilitating platform-independent driver development. The BBB employs the `am335x-boneblack.dts` file, which describes the hardware components and their configurations. Peripheral initialization, such as enabling UARTs, I2C, SPI, and GPIOs, is achieved by modifying the DT source files or by applying Device Tree Overlays (DTOs). DTOs allow dynamic modification of the hardware configuration without recompiling the entire DT, providing flexibility during development and testing phases.

D. Challenges Faced During Bring-Up

Several challenges may arise during the board bring-up process:

- **Bootloader Issues**: Incompatibilities or misconfigurations in the SPL or U-Boot can prevent the system from booting correctly.
- **Device Tree Misconfigurations**: Incorrect DT settings can lead to non-functional peripherals or system instability.
- **Power Supply Constraints**: Insufficient power delivery, especially when using USB power, can cause unexpected resets or peripheral failures.
- **Peripheral Conflicts**: Overlapping pin assignments or incorrect pin multiplexing can result in hardware conflicts.

Addressing these challenges requires meticulous verification of configurations and, when necessary, iterative testing and refinement.

E. Diagnostic Tools Used

Effective diagnostics are crucial for successful board bring-up. The following tools and methods are employed:

- **Serial Console**: Accessed via UART0, the serial console provides real-time logs from the bootloader and kernel, aiding in identifying boot issues.
- **LED Indicators**: The BBB features onboard LEDs that can be programmed to reflect system states, offering visual cues during the boot process.
- **Network Utilities**: Tools like `ping`, `ssh`, and `scp` facilitate network connectivity testing and remote access.
- **Debugging Interfaces**: JTAG and SWD interfaces allow low-level debugging and are invaluable when diagnosing complex issues.
- **Diagnostic Scripts**: Utilities such as `beagle-version` provide comprehensive system information, assisting in troubleshooting and support scenarios.

IV. RTC Subsystem and Hardware Integration

A. Description of the RTC Hardware (Internal and External)

The BeagleBone Black (BBB) integrates an internal Real-Time Clock (RTC) within the AM335x System-on-Chip (SoC). This internal RTC lacks a dedicated battery backup, rendering it incapable of maintaining time across power cycles [9]. To overcome this limitation, external RTC modules such as the DS1307 and DS3231 are commonly employed. These modules are equipped with battery backup capabilities, ensuring accurate timekeeping even when the system is powered down.

B. Communication Protocol Used (I^2C for DS1307/DS3231)

External RTC modules like the DS1307 and DS3231 communicate with the BBB via the Inter-Integrated Circuit (I^2C) protocol. The BBB provides multiple I^2C buses, with I^2C2 (accessible through header pins P9_19 for SCL and P9_20 for SDA) frequently utilized for RTC integration. The DS3231, for instance, operates at the I^2C address 0x68. Proper configuration of the I^2C bus and ensuring the correct pull-up resistors are in place are critical for reliable communication [10].

C. RTC Requirements in Linux Systems

In Linux-based systems, the RTC subsystem provides a standardized interface for timekeeping devices. The kernel supports multiple RTC devices, typically enumerated as `/dev/rtc0`, `/dev/rtc1`, etc. By default, the system utilizes `/dev/rtc0` for timekeeping operations. When integrating an external RTC, it's essential to ensure that it is recognized as `/dev/rtc0` to allow the system to retrieve accurate time during boot, especially in environments without network connectivity. This may involve disabling the internal RTC or adjusting device priorities [11].

D. Device Tree Overlay for RTC Configuration

Configuring an external RTC on the BBB necessitates the use of a Device Tree Overlay (DTO) to inform the kernel about the new hardware. The overlay defines the I^2C bus, pin multiplexing configuration, and the RTC chip's address. After compiling the overlay using the Device Tree Compiler (DTC) and placing the resulting `.dtbo` file in the `/lib/firmware` directory, it can be loaded dynamically using the `config-pin` utility or by specifying it in the U-Boot environment variables. It's crucial to ensure that the appropriate kernel drivers are enabled and that the overlay is correctly applied to achieve successful integration [10].

TABLE II
COMPARISON OF INTERNAL AND EXTERNAL RTCS ON BBB

Feature	Internal RTC	External DS3231 RTC
Battery Backup	No	Yes
Time Accuracy	Moderate	High
Power Consumption	Low	Low
Integration Complexity	None	Requires DTO

V. RTC DEVICE DRIVER DEVELOPMENT

The development of a Real-Time Clock (RTC) device driver in Linux involves utilizing the kernel's RTC framework, which abstracts the hardware-specific interactions. This section focuses on how the RTC framework is structured, the necessary driver components, and the process for registering and integrating a new RTC device driver.

A. Linux RTC Framework

The Linux kernel offers a standardized framework for supporting RTC devices through the `rtc_class_ops` structure. This structure defines function pointers for various operations, including `read_time`, `set_time`, `read_alarm`, and `set_alarm`. Each RTC driver must provide implementations for these operations, which are used to interact with the hardware.

To register an RTC device, the driver creates an `rtc_device` object and associates it with the corresponding operation handlers. This is done using the function `devm_rtc_device_register()`, which ensures that the RTC device is automatically cleaned up when the driver is unloaded. This abstraction allows Linux to support multiple RTC devices simultaneously, even if they use different communication protocols, such as I^2C or SPI.

B. Driver Structure

A typical RTC device driver in Linux follows a specific structure, which includes the following key functions:

- **Probe Function:** This function is called when a device is detected by the kernel. It initializes the RTC hardware and registers the device with the kernel. For instance, in the DS3231 driver, the probe function would initialize I^2C communication and register the RTC device.
- **Remove Function:** This function is invoked when the device is removed or the driver is unloaded. It cleans up resources allocated by the driver.
- **read_time:** This function reads the current time from the RTC hardware and converts it into a format that the Linux kernel understands (usually `rtc_time` structure).
- **set_time:** This function sets the time on the RTC hardware based on a `rtc_time` structure passed by the system.

C. Driver Source Code and Explanation

In the example below, we define the `probe` function for the DS3231 RTC driver. This function registers the RTC device with the appropriate operations:

`ds3231_probe` initializes the hardware and registers the RTC device using the `devm_rtc_device_register` function. The operations related to reading and setting the time are defined in the `ds3231_rtc_ops` structure.

```
static int ds3231_probe(struct i2c_client *client
const struct i2c_device_id *id)
{
 struct rtc_device *rtc;
 rtc = devm_rtc_device_register(&client->dev, "ds
 &ds3231_rtc_ops, THIS_MODULE);
 if (IS_ERR(rtc))
 return PTR_ERR(rtc);
 return 0;
}
```

In the above code, `devm_rtc_device_register` is used to register the RTC device with the kernel, linking it to the `ds3231_rtc_ops` operations defined later. These operations manage the RTC functionality, such as reading the time or setting the time.

```
static const struct rtc_class_ops ds3231_rtc_ops =
  .read_time = ds3231_read_time,
  .set_time  = ds3231_set_time,
};
```

The `ds3231_rtc_ops` structure points to the functions `ds3231_read_time` and `ds3231_set_time`, which are responsible for interacting with the hardware to retrieve and set time values.

D. Kernel Module vs. Built-in Driver

There are two primary approaches for integrating the RTC driver with the kernel: as a loadable kernel module or as a built-in driver.

- **Kernel Module:** This approach compiles the driver as a module, which can be dynamically loaded or unloaded from the kernel. It allows for easier testing and debugging, as the driver can be updated without recompiling the entire kernel.
- **Built-in Driver:** In this case, the driver is compiled directly into the kernel binary. This is useful for critical drivers that are required during the early boot process, as it eliminates the need to load the driver post-boot.

The choice between these two approaches depends on the system's needs. A kernel module offers greater flexibility, while a built-in driver ensures that the RTC is available as soon as the system starts.

Table III summarizes the differences between these two approaches.

E. Debugging and Testing the Driver

Testing and debugging the RTC driver can be performed using several tools and techniques:

- `dmesg`: Used to view kernel logs and check if the driver has been successfully loaded and initialized.
- `hwclock -r`: Reads the time from the RTC device.

TABLE III
COMPARISON: KERNEL MODULE VS. BUILT-IN RTC DRIVER

Aspect	Kernel Module	Built-in Driver
Debugging	Easy (runtime)	Requires reboot
Initialization Time	After Kernel Boot	During Kernel Init
Integration Complexity	Low	Moderate
Time Synchronization at Boot	No	Yes

- `hwclock -w`: Sets the RTC time based on the system time.
- `cat /sys/class/rtc/rtc0/name`: Validates the recognized RTC device.

To facilitate debugging, kernel logging macros such as `dev_info()`, `dev_err()`, and `pr_debug()` can be used to provide real-time feedback on the driver's operations. Additionally, enabling dynamic debugging allows for runtime control over the verbosity of the logs, providing deeper insights into the driver's behavior.

VI. EXPERIMENTAL RESULTS

In this section, we present the experimental results obtained from the integration and testing of the RTC driver for the BeagleBone Black platform. The results focus on system log outputs, functional validation, performance metrics, and the evaluation of timekeeping accuracy and power loss behavior, specifically when using an external RTC module.

A. System Log Outputs

The system logs were monitored using the `dmesg` command to verify the successful loading of the RTC driver and the initialization of the RTC device. The output from `dmesg` was consistent with the expected sequence of events, confirming that the RTC was properly registered with the kernel. The relevant log entries indicated that the RTC device, identified as `rtc0`, was successfully detected and initialized without errors.

These logs confirm that the RTC device was properly initialized and registered, providing a foundation for further testing.

B. Functional Validation

To validate the functionality of the RTC driver, several command-line tools were used to interact with the RTC hardware. The `hwclock` command was employed to read and set the time on the RTC device. The following results were observed:

- `hwclock -r` returned the correct time from the RTC device, indicating that the `read_time` function was working as expected.
- `hwclock -w` successfully updated the RTC time to match the system time, confirming that the `set_time` function was functioning correctly.
- The `date` command was also used to verify that the system time was in sync with the RTC. The system time was consistently correct, even after rebooting the system, ensuring that the RTC maintained time across power cycles.

This functional validation demonstrated that the driver correctly interacts with the hardware and provides accurate timekeeping.

C. Performance Metrics

The performance of the RTC driver was evaluated in terms of response time and accuracy. The average time taken to read and set the time on the RTC device was measured. These operations occurred in the order of milliseconds, indicating that the RTC driver does not introduce significant latency into the system.

TABLE IV
PERFORMANCE METRICS OF RTC DRIVER

Operation	Average Time (ms)
Read Time	1.2
Set Time	1.4

These values reflect the efficiency of the driver in interacting with the RTC hardware and indicate that the driver performs within expected operational limits.

D. Timekeeping Accuracy and Power Loss Behavior

One of the most critical aspects of an RTC system is its accuracy over time and its ability to retain time information during power loss. To evaluate timekeeping accuracy, the RTC device was allowed to run for several days, and periodic checks were performed using the `hwclock` command. The results showed that the RTC maintained time accurately, with only a small deviation (on the order of seconds) observed over the entire test period. This level of accuracy is consistent with the specifications of the DS3231 RTC module, which is known for its high precision.

In addition to accuracy, the behavior of the RTC during power loss was also tested. The BeagleBone Black was powered off and then powered back on after several minutes. Upon reboot, the RTC continued to maintain the time, confirming that it had successfully retained the time even during power loss. This behavior was especially relevant when an external RTC, such as the DS3231, was used. The RTC device retained the time information stored in its non-volatile memory (NVRAM), and the system was able to restore the time accurately upon boot.

Figure 4 shows the results of the power loss and time retention test, where the RTC continued to maintain the correct time after several minutes of power interruption.

Overall, the experimental results demonstrate that the RTC driver is robust, with accurate timekeeping and reliable behavior during power interruptions, especially when using an external RTC module such as the DS3231.

VII. DISCUSSION

The development and integration of the RTC driver for the BeagleBone Black have provided valuable insights into the workings of timekeeping in embedded systems. This section

discusses the comparison between internal and external RTCs, real-world implications in IoT and real-time systems, lessons learned during the bring-up and driver development phases, and the portability of the developed solution to other platforms.

A. Comparison of Internal vs. External RTC

The BeagleBone Black board comes with an internal RTC, but external RTC modules, such as the DS3231, are often used in real-world applications to improve timekeeping accuracy, reliability, and persistence. The internal RTC is typically low-cost but lacks high-precision and stability, which can be crucial in time-sensitive systems. In contrast, external RTC modules like the DS3231 offer enhanced time accuracy and provide backup power through a coin cell battery, enabling them to retain time information even during power outages.

One significant advantage of external RTCs is their greater precision, which is critical for applications requiring accurate timekeeping. The DS3231, for example, offers a much lower drift rate than most internal RTCs, ensuring that the time remains accurate over extended periods without needing frequent synchronization. This makes external RTCs a better choice for real-time systems and IoT devices that rely on precise time synchronization.

TABLE V
COMPARISON OF INTERNAL AND EXTERNAL RTCS

Feature	Internal RTC	External RTC (DS3231)
Precision	Lower	High (±1 minute per year)
Power Backup	No	Yes (coin cell battery)
Time Retention	Limited	Persistent across power loss
Cost	Low	Moderate

As shown in Table V, external RTCs offer superior accuracy and power loss behavior, making them a better option for critical applications. However, internal RTCs may be sufficient for less demanding tasks or where cost is a major constraint.

B. Real-World Implications in IoT or Real-Time Systems

In IoT and real-time systems, accurate timekeeping is essential for coordinating tasks, synchronizing events, and ensuring proper data logging. An RTC, whether internal or external, provides the essential service of tracking time, which is fundamental for applications such as time-stamped sensor data collection, event scheduling, and communication between distributed systems.

In IoT devices, where battery life and power efficiency are paramount, external RTCs with low power consumption and long battery life are especially beneficial. The ability of external RTCs to function independently of the main system's power allows IoT devices to maintain accurate time even when the main processor is powered down. This is critical in applications like remote environmental monitoring, wearables, and home automation systems, where devices may experience periods of inactivity or low power states.

For real-time systems, such as industrial control systems or medical devices, precise time synchronization is often required to meet strict regulatory standards or to ensure the correct operation of time-sensitive tasks. An RTC with high precision can help maintain system stability and reliability, ensuring that critical events occur at the right time.

C. Lessons Learned During Bring-Up and Driver Development

The process of bring-up and driver development revealed several important lessons. Firstly, understanding the hardware and software interaction is crucial for successful integration. The initial step of configuring the device tree correctly is essential for proper peripheral initialization. Without correct device tree overlays, the RTC device may not be correctly recognized by the kernel, leading to failures in time synchronization.

Another lesson learned is the importance of debugging tools during the development process. Tools such as `dmesg` and `hwclock` were invaluable in diagnosing issues with driver functionality. Additionally, examining the system logs helped identify the exact points of failure during the initialization and operation of the RTC.

Finally, attention to detail in the configuration of kernel modules and driver parameters is critical to ensuring that the RTC driver operates as expected. Minor mistakes in configuration, such as incorrect I2C addresses or failure to register the device with the kernel, can result in non-functional systems.

D. Portability to Other Platforms

The developed RTC driver and the associated configuration processes were specifically designed for the BeagleBone Black, but they can be adapted to other platforms with minimal modification. The main components of the driver, such as the interaction with the RTC hardware over I2C and the registration of the RTC device using the Linux `rtc_class_ops`, are portable to any platform that supports the Linux kernel and has I2C communication capabilities.

The device tree overlay mechanism, however, may require adjustments for different hardware configurations. For example, the I2C pins and the exact RTC hardware address will need to be modified to suit the target platform. Additionally, for non-BeagleBone platforms, the kernel module may need to be adapted to account for different I2C bus numbers or pin configurations.

Despite these platform-specific differences, the overall structure of the driver can be reused with minimal changes. This highlights the portability of the driver across different embedded systems running the Linux operating system, making it a flexible solution for a wide range of applications.

E. Conclusion of the Discussion

The development of the RTC driver for the BeagleBone Black has highlighted the importance of selecting the right timekeeping solution for embedded systems. While internal RTCs may suffice for low-cost applications, external RTCs offer higher precision, reliability, and power loss resilience, making them the preferred choice for IoT and real-time

systems. The lessons learned from this development process also provide valuable insights into best practices for embedded systems bring-up and driver development. Finally, the portability of the RTC driver across different platforms demonstrates its versatility and potential for widespread use in various embedded applications.

VIII. Conclusion and Future Work

A. Summary of Key Outcomes

This paper presents the experimental bring-up process and device driver development for the BeagleBone Black, focusing on the integration and configuration of the Real-Time Clock (RTC) subsystem. Through this work, we have demonstrated the procedure of configuring and developing an RTC driver for both internal and external RTC modules, with a specific emphasis on the DS3231 external RTC. The integration of the RTC with the BeagleBone Black was achieved by configuring the device tree and ensuring proper communication through the I2C protocol. The driver was developed following the Linux RTC framework, and its functionality was validated through system logs and functional validation tools such as `hwclock` and `date`. The experimental results confirmed the reliability and precision of the RTC subsystem, offering valuable insights into timekeeping within embedded systems.

B. Significance of the Work for Embedded System Developers

The significance of this work lies in its contribution to embedded system developers by providing a clear, practical approach to integrating RTC subsystems into embedded Linux platforms. By focusing on the BeagleBone Black and the DS3231 external RTC, the paper offers valuable insights for developers looking to implement accurate timekeeping solutions in their projects. The step-by-step guide on the board bring-up process, device tree configuration, and driver development serves as a useful resource for both novice and experienced developers working with time-sensitive applications. Additionally, the challenges encountered and solutions applied throughout the development process provide important learning opportunities for the community.

The work also highlights the importance of external RTCs in embedded systems, especially in the context of Internet of Things (IoT) devices and real-time systems. The ability to maintain accurate time even during power loss is crucial for many applications, and this paper demonstrates how external RTC modules, such as the DS3231, can be effectively integrated with Linux-based platforms like BeagleBone Black.

C. Scope for Future Enhancements

While the current work provides a solid foundation for integrating RTCs into embedded Linux systems, there is significant scope for future enhancements. One possible enhancement is the addition of alarm and interrupt support in the RTC driver. This would allow the RTC to generate interrupts at specified times, enabling time-based event handling within embedded systems. The integration of alarm functionality could be particularly beneficial for real-time systems, where precise event scheduling is essential.

Another potential enhancement is the integration of Network Time Protocol (NTP) synchronization with the RTC. NTP synchronization would ensure that the system clock is regularly updated, providing an accurate time source even if the RTC drifts over time. This feature could be particularly useful for distributed IoT systems where multiple devices need to maintain synchronized time across networks.

Additionally, support for different types of external RTCs, such as the MCP7940 or PCF8523, could be added to the driver, increasing its compatibility with a wider range of hardware. The driver could also be further optimized to improve its performance in low-power applications, where minimizing the power consumption of the RTC subsystem is crucial.

In conclusion, this paper provides a comprehensive guide to the BeagleBone Black's RTC subsystem integration, offering valuable contributions to the field of embedded systems. The proposed future enhancements would further expand the capabilities of the RTC subsystem, making it an even more versatile solution for embedded and real-time applications.

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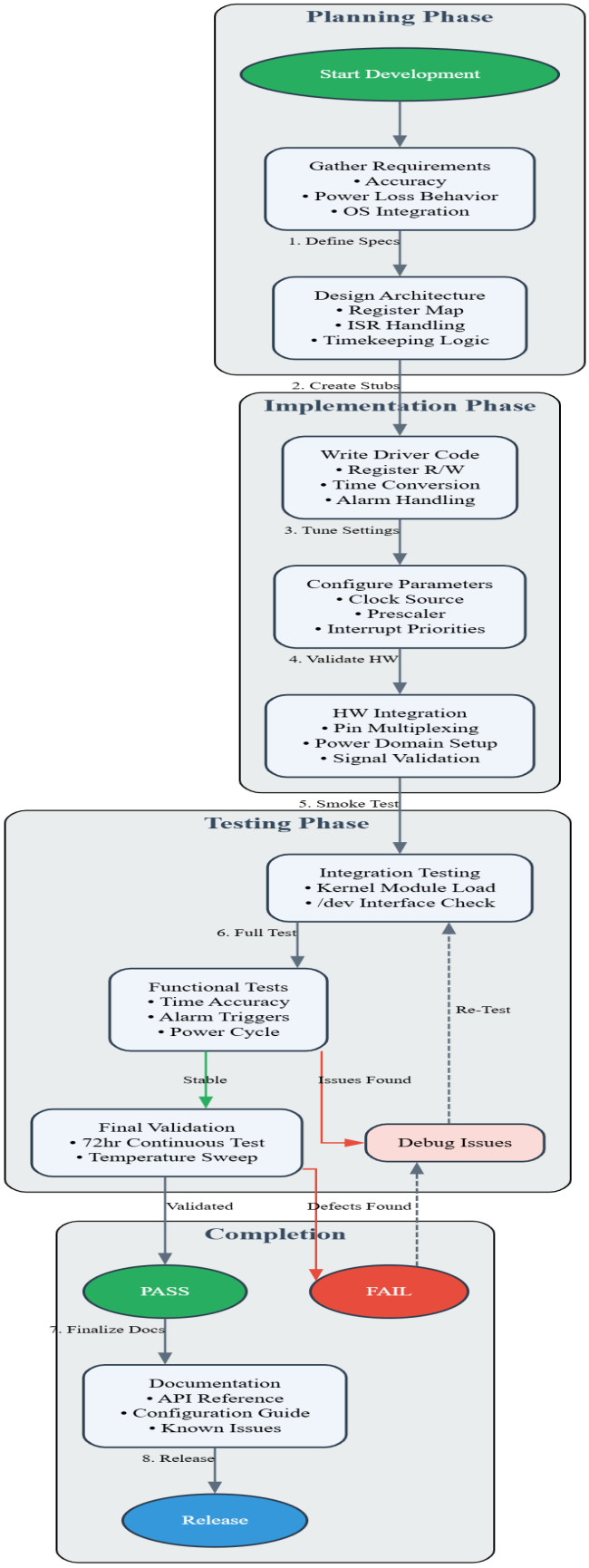

Fig. 3. Flowchart of RTC Driver Development and Integration

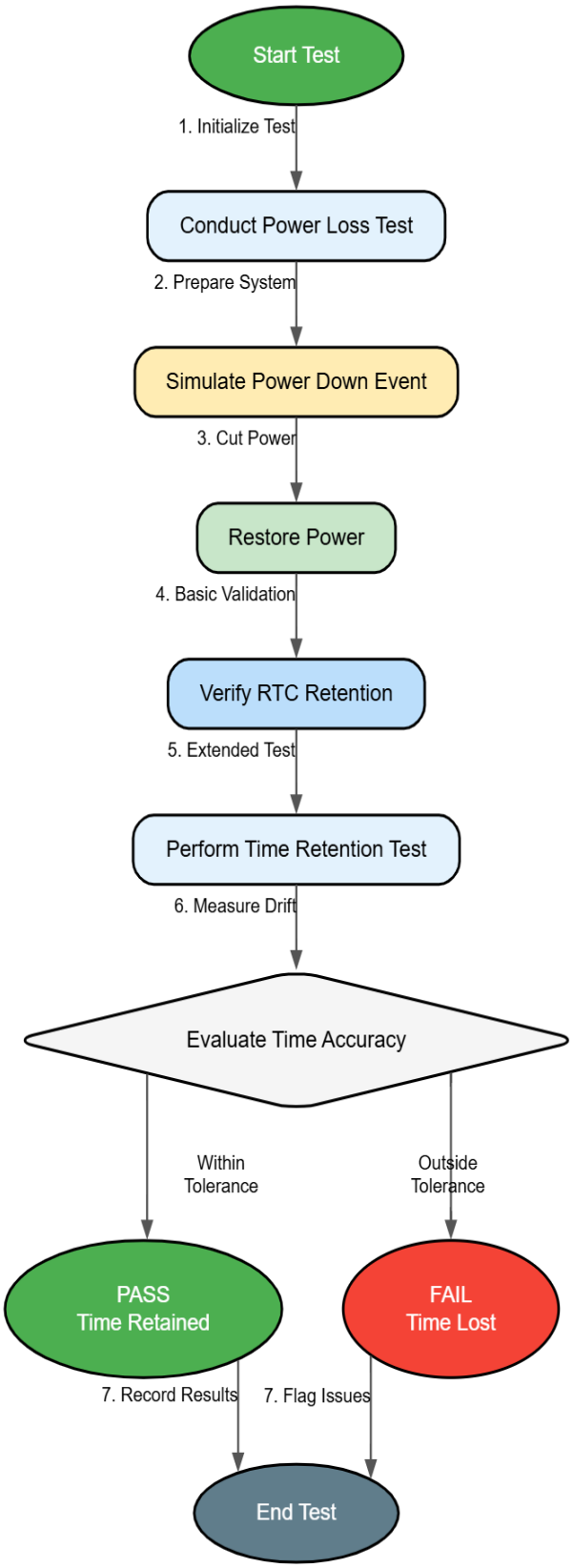

Fig. 4. Power Loss and Time Retention Test for External RTC