WIP: Transparent Standby for Low-Power, Resource-Constrained Embedded Systems

A Programming Language-Based Approach

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Abstract

Standby efficiency for connected devices is one of the priorities of the *G20's Energy Efficiency Action Plan*. We propose transparent programming language mechanisms to enforce that applications remain in the deepest standby modes for the longest periods of time. We extend the synchronous programming language Céu with support for interrupt service routines and with a simple power management runtime. We provide device drivers based on these primitives on top of which applications can be built to take advantage of standby automatically. We also show that programs in Céu can keep a sequential structure to lower the barrier of adoption, even when applications require non-trivial concurrent behavior.

CCS Concepts • **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability;

Keywords   ACM proceedings, LaTeX, text tagging

According to the International Energy Agency (IEA), the number of network-connected devices is expected to reach 50 billion by 2020 with the expansion of the Internet of Things (IoT) [6]. However, most of the energy to power these devices will be consumed in *standby mode*, i.e., when they are neither transmitting or processing data. For instance, standby power currently accounts for 10–15% of residential electricity consumption, and CO_2 emissions related to standby are equivalent to those of 1 million cars [6, 7]. The projected growth of IoT devices, together with the surprising effects of

standby consumption, made network standby efficiency one of the six pillars of the *G20's Energy Efficiency Action Plan*[1].

Given the projected scale of the IoT and the role of low-power standby towards energy efficiency, this paper has the following goals:

1. Address energy efficiency through extensive use of standby.
2. Target low-power, resource-constrained embedded architectures that form the IoT.
3. Provide standby mechanisms at the programming language level that scale to all applications.
4. Support transparent/non-intrusive standby mechanisms that reduce barriers of adoption.

Our approach lies at the bottom of the software development layers—programming language mechanisms—meaning that *all* applications take advantage of low-power standby modes automatically, without extra programming efforts. We extend the synchronous programming language Céu [9, 10] with support for interrupt service routines (ISRs) and with a simple power management runtime (PMR).

Each supported microcontroller requires bindings in C for the ISRs and PMR, and each peripheral requires a driver in Céu. These are write-once code that are typically packaged and distributed in a software development kit (SDK). Then, all new applications built on top of these drivers take advantage of standby automatically. As a proof of concept, we provide an open source SDK with support for 8-bit *AVR/ATmega* and 32-bit *ARM/Cortex-M0* microcontrollers, and a variety of peripherals, such as for GPIO, A/D converter, USART, SPI, and the nRF24L01 transceiver. We developed a number of simple applications using these peripherals concurrently and could verify that the applications remain in the deepest standby modes for the longest periods of time.

In Section 1, we compare the structure of programs in Céu and Arduino [2], whose primary goal is to reduce the barrier of adoption for a non-technical audience (e.g., designers and artists). We show that we can keep the intended sequential reasoning of Arduino even when applications require non-trivial concurrent behavior. In Section 2, we discuss the software infrastructure that allows for unmmodified programs in Céu to take advantage of standby automatically. In Section 3, we discuss future work and conclude the paper.

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[1]G20's Energy Efficiency Action Plan: https://www.iea-4e.org/projects/g20

```
111  while (1) {          1  loop do                         166
112    delay(1000);       2    await 1s;                      167
113    int v =            3    var int v =                    168
114      analogRead();    4      await AnalogRead();          169
115    radioWrite(v);     5    await RadioWrite(v);           170
116  }                    6  end                              171
```

[a] Version in Arduino	[b] Version in Céu

Figure 1. Sequence of I/O operations running in a loop.

1 The Structured Synchronous Programming Language Céu

Céu is a Esterel-based [9] reactive programming language targeting resource-constrained embedded systems [10]. It is grounded on the synchronous concurrency model, which has been successfully adopted in the context of hard real-time systems such as avionics and automobiles industry since the 80's [3]. The synchronous model trades power for reliability and has a simpler model of time that suits most requirements of IoT applications. On the one hand, this model cannot directly express time-consuming computations, such as compression and cryptography algorithms, which are typically either absent or delegated to auxiliary chips in the context of the IoT. On the other hand, all reactions to the external environment are guaranteed to be computed in bounded time, ensuring that applications always reach an idle state amenable to standby mode. Overall, Céu aims to offer a concurrent, safe, and expressive alternative to C with the characteristics that follow:

Reactive: code only executes in reactions to events.
Structured: programs use structured control mechanisms, such as await (to suspend a line of execution), and par (to combine multiple lines of execution).
Synchronous: reactions run atomically and to completion on each line of execution, i.e., there's no implicit preemption or real parallelism.

Structured reactive programming lets developers write code in direct style, recovering from the inversion of control imposed by event-driven execution [1, 5, 8].

A Motivating Example

Figure 1.a shows a straightforward, easy-to-read program chunk in Arduino that executes forever in a loop a sequence of operations as follows: waits for 1 second (ln. 2), performs an A/D conversion (ln. 3–4), and broadcasts the read value (ln. 5). Figure 1.b shows the same chunk in Céu, with the noteworthy difference that operations that interact with the environment and take time use the await keyword. The traditional structured paradigm encouraged in Arduino (with blocks, loops, and sequences) allows for simple and readable code, avoiding the complexity of dealing with ISRs. However,

```
uint32_t prv =          1  par/or do                        166
  millis();             2    await RadioAvail();             167
while (1) {             3  with                              168
  if (radioAvail()) {   4    loop do                         169
    break;              5      await 1s;                     170
  }                     6      var int v =                   171
  uint32_t cur =        7        await AnalogRead();         172
    millis();           8      await RadioWrite(v);          173
  if (cur>prv+1000) {   9    end                             174
    prv = cur;         10  end                               175
    int v =            11                                    176
      analogRead();    12                                    177
    radioWrite(v);     13                                    178
  }                    14                                    179
}                      15  .                                 180
```

[a] Version in Arduino	[b] Version in Céu

Figure 2. Achieving concurrency between I/O operations.

the use of blocking operations, such as delay(1000) (ln. 2), prevents that other operations execute concurrently.

Suppose that we now want to immediately abort the loop in Figure 1.a at any time, as soon as a radio message arrives. Since the message might arrive concurrently with any of the blocking operations, we need to change the structure of the program. Figure 2.a changes the blocking delay to the polling millis, which immediately returns the number of milliseconds since the reset. Now, we start by registering the current time (ln. 1–2) and, on each loop iteration, we recheck the time to see if one second has elapsed (ln. 7–9). Since these operations are non-blocking, we can intercalate their execution with checks for message arrivals (ln. 4–6). If the time is up, we start counting it again (ln. 10) before proceeding to the original operations in sequence (ln. 11–13). The original structured style has been drastically violated to accommodate concurrency. In the example, we only adapted the delay operation, but the other blocking operations (analogRead and radioWrite) would also need to be changed to achieve maximum concurrency. Alternatively, we could resort to ISRs or implement an event-driven scheduler to handle the operations [4], but ultimately, the program readability would still be compromised.

The program in Figure 2.b in Céu extends the one in Figure 1.b to accommodate concurrency. The original code remains unmodified (ln. 4–9) and concurrency is achieved through the par/or construct, which creates two lines of execution and terminates when either of them terminates, aborting the other automatically. This approach preserves the sequential, easy-to-read style while introducing concurrency seamlessly.

Standby Considerations

The structure of the program in Figure 2.b also indicates which peripherals are active at a given time. For instance, when the program is awaiting concurrently in lines 2 and 7, only the radio transceiver and A/D converter can awake the program. Hence, the language runtime can choose the most energy-efficient sleep mode that allows these peripherals to awake the microcontroller from associated interrupts. Since the semantics of Céu enforces the program to always reach `await` statements in all active lines of execution, it is always possible to put the microcontroller into the optimal sleep mode after each reaction to the environment.

2 Standby Infrastructure

In order to empower the example in Figure 2.b with automatic standby, we developed some extensions to Céu:

- Make the runtime of Céu to be interrupt driven and to put the microcontroller in standby after each reaction to the environment.
- Provide operations for the drivers to indicate which interrupts can awake the program.
- Support ISRs in Céu to generate input events to the program.

Figure 3 shows the driver for the A/D converter in Céu. This code is specific to the *ATmega328p* microcontroller and must be adapted to work in other platforms. For simplicity, we assume in the paper that the converter has a single channel to avoid having to deal with multiplexing.

The driver exposes raw I/O events (ln. 3–4) that only deal with low-level port manipulation in the microcontroller. Output events are triggered with the `emit` keyword (ln. 29), while input events are captured with the `await` keyword (ln. 30). The output event `ADC_REQUEST` (ln. 9–15) enables ADC interrupts and starts an analog-to-digital conversion asynchronously in the preipheral for the single channel `A0`. Any code in between `{` and `}` is treated as an inline *C* chunk, allowing for easy integration with *C* for low-level operations.

The `async/isr` construct of Céu defines an ISR which executes asynchronously with the program when the specified interrupt occurs. Only ISRs can emit input events to the program. In the example, we define an ISR to handle `ADC` interrupts which fire whenever a conversion is complete (ln. 17–21). Although the ISR body executes asynchronously on interrupts, the input emission (ln. 20) only takes effect on a subsequent reaction, when the synchronous part of the program is idle. This way, race conditions are only possible with async/isr blocks, which are typically hidden inside device drivers. Céu also provides an `atomic` primitive to protect critical sections of code.

The low-level events are the pieces that vary among platforms. A driver can also expose a higher-level portable abstraction to client code. In the example, the `AnalogRead` abstraction (ln. 23–33) takes care of starting and awaiting the

```
1  // Exposed driver functionality
2
3  output void ADC_REQUEST; // low-level request
4  input  int  ADC_DONE;    // low-level response
5  code AnalogRead (void) -> int; // high-level abstraction
6
7  // Driver implementation
8
9  output void ADC_REQUEST do
10   {
11     ADMUX = 0x40 | (A0 & 0x07);
12     bitSet(ADCSRA, ADIE); // enables interrupt
13     bitSet(ADCSRA, ADSC); // starts the conversion
14   }
15 end
16
17 async/isr {ADC_vect_num} do
18   { bitClear(ADCSRA, ADIE); } // disables interrupt
19   var int value = {ADC}; // reads register with the value
20   emit ADC_DONE(value);
21 end
22
23 code AnalogRead (void) -> int do
24   {PM_SET(PM_ADC, 1);}
25   do finalize with
26       {PM_SET(PM_ADC, 0);}
27   end
28
29   emit ADC_REQUEST;
30   var int value = await ADC_DONE;
31
32   escape value;
33 end
```

Figure 3. Céu driver for the *ATmega328p* A/D converter.

conversion (ln. 29–30), as well as dealing with the power management runtime (PMR). The `PM_SET(PM_ADC,1)` (ln. 24) tells the system that, when entering in sleep mode, the `ADC` must be kept running. The `PM_SET(PM_ADC,0)` inside the `finalize` clause (ln. 25–27) releases the `ADC` subsystem from the PMR.

The `finalize` construct of Céu executes the nested code whenever its enclosing block terminates or is aborted externally. The example of Figure 2.b invokes the `AnalogRead` abstraction (ln. 7) concurrently with `RadioAvail` (ln. 2). It is possible that the `AnalogRead` terminates normally or that a radio message arrives during the A/D conversion, which causes the `AnalogRead` to abort abruptly. In either case, the `finalize` clause executes and puts the PMR in a consistent state.

The PMR also expects a platform-specific power management module to be able to put the microcontroller into the most efficient sleep mode possible. Figure 4 implements

3

```
1  #define PM_GET(dev)    bitRead(pm,dev)
2  #define PM_SET(dev,v) bitWrite(pm,dev,v)
3
4  static u32 pm = 0;
5
6  enum {
7    CEU_PM_ADC = 0,
8    CEU_PM_TIMER1,
9    <...>,
10 };
11
12 void pm_sleep (void) {
13   if (PM_GET(PM_TIMER1) || <...>) {
14     LowPower.idle(PM_GET(PM_ADC),<...>)
15   } else if (PM_GET(PM_ADC)) {
16     LowPower.adcNoiseReduction(<...>);
17   } else {
18     LowPower.powerDown(<...>);
19   }
20 }
21 }
```

Figure 4. Power management module for the *ATmega328p* microcontroller.

the `pm_sleep` function for the *ATmega328p* microcontroller which the PMR calls when the program is idle. Each device has an associated index (ln. 6–10) in the `pm` bit vector (ln. 4). The driver manipulates its device's index to indicate its state (Figure 3, ln. 24,26). The `pm_sleep` queries the vector to choose the appropriate sleep mode. In the example, if the timer is active (ln. 13), the microcontroller can only use the least efficient mode[2] (ln. 14). In the best case, e.g., if only external interrupts are required, the microcontroller can use the most efficient mode (ln. 18).

With all the standby infrastructure set, the unmodified program of Figure 2.b will automatically take advantage of the deepest sleep modes for the longest periods of time possible.

3 Conclusion and Future Work

In this work, we address standby efficiency for embedded devices at the level of programming languages. We propose a software infrastructure for the programming language Céu that encompass a power management runtime and support for interrupt service routines in the language. Our approach relies on the synchronous semantics of the language which enforces that reactions to the environment always reach an idle state amenable to standby. We then take energy-unaware programs in Céu and show that, using the proposed

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[2] We use an external library for the sleep modes: http://www.rocketscream.com/blog/2011/07/04/lightweight-low-power-arduino-library/

infrastructure, they can take advantage of the longest periods of time and deepest sleep modes possible.

In future work, in order to evaluate the gains in energy efficiency with the proposed infrastructure, we will evaluate the consumption of realistic applications. The Arduino community has an abundance of open-source projects which can be rewritten in Céu to take advantage of transparent standby. In this scenario, we can evaluate the time to rewrite, the resulting program structure, and the actual energy consumption efficiency.

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