All Eyes on Code

Using Call Graphs for WSN Software Optimization

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Motivation

µDTN: Delay-tolerant Networking Implementation for Contiki
- Bundle Protocol Stack
- Network throughput was significantly lower than expected

Common Optimization Approaches
- Standard profiling tools known from the PC
- Expert knowledge of code to “feel” bottlenecks
- Lot’s of manual hacking to find bottlenecks
- Trail-and-error optimizations

→ How can WSN software be optimized in a (more) deterministic way (using standard nodes)?
Why is performance important for WSN software?

Scarce Computational Resources
- Microcontrollers are slow and speed is increasing slowly
- WSN application complexity is rising and will continue to do so (6LoWPAN, CoAP, RPL/ROLL, etc.)

Energy Consumption
- Energy supply is usually limited and scarce
- Faster execution times allow MCU to sleep longer

→ WSN Software optimization is necessary!
How to locate performance problems in WSN code?

Need knowledge of where the node spends most if its time!

→ Have to instrument the code to collect information about function calls
Obtaining performance information for WSN code

**Static Source Code Analysis**
Does not allow conclusion on performance (in a real environment)

**Instruction Set Simulators**
Do not capture timing behaviour (especially of hardware components)

**JTAG**
Requires high read-out rate, halting the CPU and external hardware

**Manual Source Code Instrumentation**
Very good accuracy but does not scale

**Automatic Source Code Instrumentation**
Standard instrumentation does not work on microcontrollers (file I/O)
Approach in this work

1. Compiler-assisted Instrumentation of Code
   Done by the GCC compiler

2. Collect Function Call Information on the Node
   Using custom instrumentation functions

3. Transfer Collected Information to Host
   On user request, off the critical path

4. Post-process and Visualize Information
   Produce call graph image
**Call Graphs**

**Instrumentation Function**

Collects function call information (not part of the original user code)
1. Compiler-assisted Instrumentation of Code

- Compiler automatically modifies the intermediate code
- Inserts calls to *instrumentation functions* into each function
- Caller and Callee are provided as arguments

```c
void example() {
    printf("foo");
}
```

```c
void example() {
    profile_enter(...);
    printf("foo");
    profile_exit(...);
}
```
How to handle function call information?

Common Approach

- Transfer information about individual function calls
- **On the critical path**

What to do with function call information?

- Keep in RAM: 16 bytes per function call
- Store in flash: 0.4 ms per call (avg), 6 ms max
- Send via serial: 1.74 ms per call

→ Delay per call should be minimal, processing off the critical path!
How to handle function call information? (cont’d)

Aggregating call information on the node
- Collect information about individual function calls
- Aggregate all information regarding one call site (0.16 ms avg / call)

Last-In First-Out Call Stack

Sorted call site table

<table>
<thead>
<tr>
<th></th>
<th>Addr. of Caller</th>
<th>Addr. of Callee</th>
<th>Invocation Count</th>
<th>Min Execution Time</th>
<th>Max Execution Time</th>
<th>Total Execution Time</th>
</tr>
</thead>
</table>
2. Collect Function Call Information on the Node

**profile_enter**<br>(void * callee, void * caller)<br>- Record caller, callee and current time<br>- Create entry on call stack: $O(1)$

**profile_exit**<br>(void * callee, void * caller)<br>- Record current time<br>- Obtain latest entry from call stack: $O(1)$<br>- Search for call site entry: $O(\log n)$<br>- Create / update call site entry
3. Transfer Collected Information to Host

Printing out call information on user request
- Can be done off the critical path
- Timing is irrelevant

Data Format
4. Post-process and Visualize Information

- Convert function addresses to function names
- Aggregate multiple call sites within a function
- Subtract execution time from outgoing function calls
- Produce image file
Implementation and Evaluation

Implementation Target Platform

- Contiki OS
- INGA and T-Mote Sky
- GCC Toolchain

→ Not limited to either Contiki or specific hardware

Evaluation Setup

- INGA
  - MCU: Atmel Atmega 1284p (128 kB ROM, 16 kB RAM, 8 MHz)
  - Radio: Atmel AT86RF231 (IEEE 802.15.4)
  - Various sensors (accelerometer, gyroscope, pressure, etc.)
- Contiki and μDTN
Evaluation Use Cases

Worst-case Situations

- **CRC-16** Calculate CRC Checksum over 1 MB 100 % load
- **Fibonacci** Recursive calculation of 27 elements 100 % load
- **One-way** Throughput test using μDTN 100 % load
- **Pingpong** Roundtrip throughput test using μDTN 100 % load

Typical WSN Use Cases

- **Sample-Send** Typical WSN use case using μDTN low load
Performance Implications of Instrumentation

→ Overhead strongly depends on number of function calls
RAM and ROM Overhead

RAM Overhead
- 8 bytes per call stack entry; typically 160 bytes
- 16 bytes per call site; typically 720 bytes

ROM Overhead
- 62 bytes for instrumentation functions
- 58 bytes per instrumented function
- Typical: 14,562 bytes for 250 instrumented functions

→ RAM and ROM overhead is manageable on modern nodes
Conclusions

WSN software optimization is difficult but increasingly important

Instrumented code on nodes can be used to produce call graphs
- Call graphs allow to visually identify potential performance bottlenecks
- Code running on the nodes allows to capture the real execution environment in great detail

Overhead is manageable on modern nodes
- Performance impact depends on the number of function calls
- ROM and RAM overhead is manageable on modern nodes
Exemplary Call Graph 2

uDTN-hash-test.c
process_thread_test_process() (unprofiled)

hash_xxfast.c
hash_xxfast_convenience_ptr()
min: 0.488ms max: 0.488ms
1.221ms
8 calls

hash_xxfast.c
hash_xxfast_convenience()
min: 0.244ms max: 0.732ms
1641.602ms
10008 calls

hash_xxfast.c
hash_xxfast_buffer()
min: 0.244ms max: 0.732ms
3255.859ms
10024 calls

4.899s/7.143s profiled
Exemplary Call Graph 3