Protothreads: Simplifying Event Driven Programming of Memory-Constrained Embedded Systems

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Introduction: Event-driven vs Multithread?

- Many operating systems for sensor networks (TinyOS, Contiki, SOS) use event-driven programming model instead of traditional multithreaded approach
- Event-driven systems support high level of concurrency with little RAM
  - Single stack
  - Sensor nodes have limited RAM (few kilobytes)
- Multithreading is difficult due to limited RAM
  - Per-thread stack (Default stack size for each stack in MANTIS is 128 bytes)
  - Expensive context switching, thread-scheduling, synchronization, reentrancy etc.
  - Can limit concurrency

Protothreads: Motivation

- An event-driven model does not support blocking wait abstraction
- Programming is difficult – a logically blocking sequence must be written in a state machine style
  - Split phase operation in TinyOS
- Thus many practical event-based programs are difficult to understand
- Protothreads was originally developed for managing the complexity of state machines in the event-driven uIP embedded TCP/IP stack

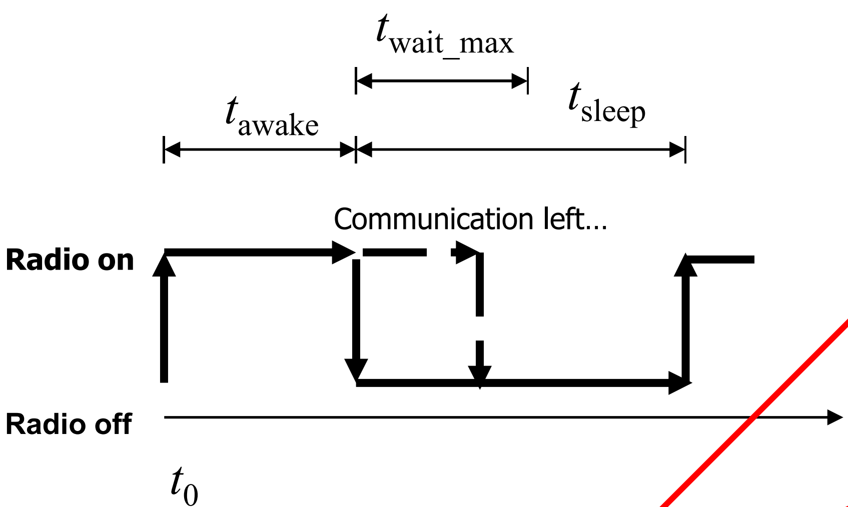
Protothreads: Goals

- Simplify programming by reducing or eliminating state machine management
- Negligible RAM overhead
- Not intended to replace event-driven systems
  - rather be able to use protothreads on top of event-driven system if state management becomes difficult

Protothreads

- Protothreads provide conditional blocking abstractions to simplify programming for memory-constrained embedded devices
  - The blocking wait semantics allow linear sequencing of statements in event-driven systems
- Protothreads are stackless–all protothreads in a system run on the same stack, which is rewound every time a protothread blocks.
- A protothread is invoked by repeated calls to the function in which it runs

Example: Hypothetical MAC

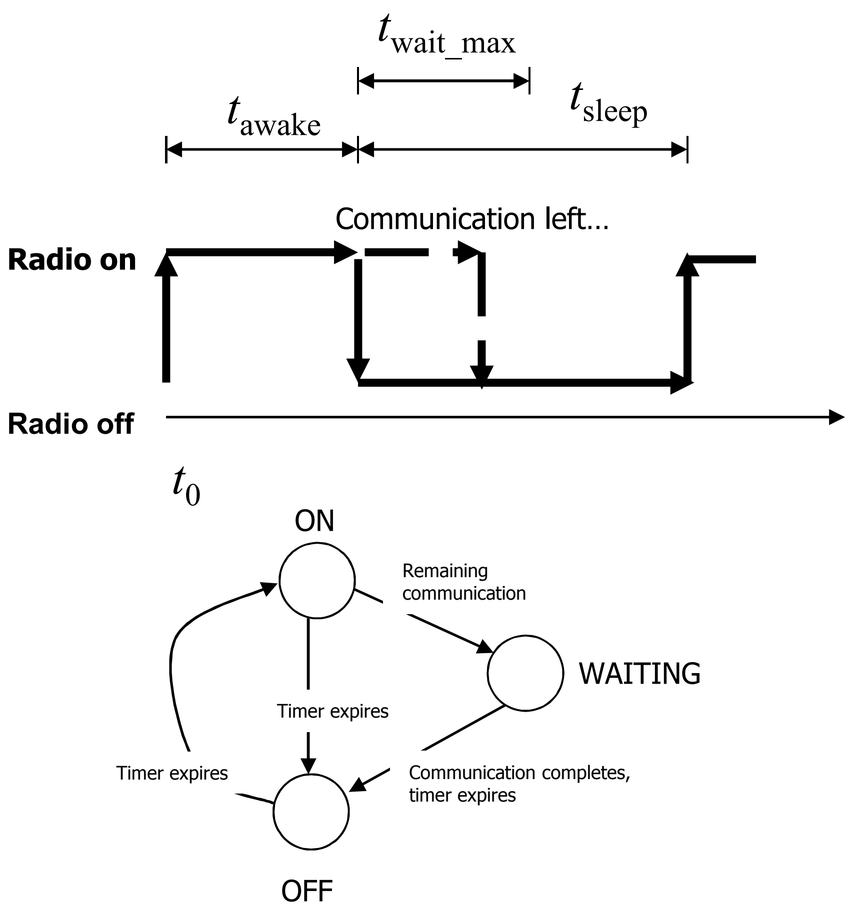


1. Turn radio on.
2. Wait until $t = t\_0 + t\_awake$.
3. If communication has not completed, wait until it has completed or $t = t\_0 + t\_awake + t\_wait\_max$.
4. Turn the radio off. Wait until $t = t\_0 + t\_awake + t\_sleep$.
5. Repeat from step 1.

No blocking wait!

Problem: With events, we cannot implement this as a five-step program!

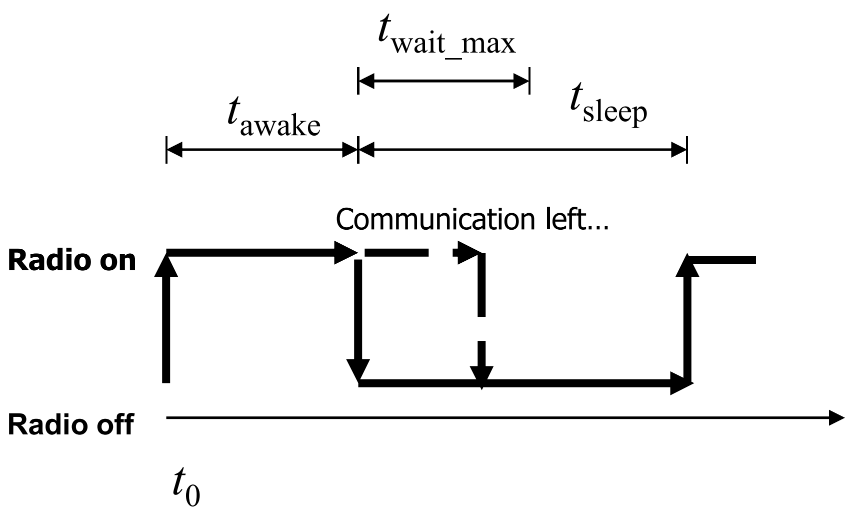
Event-driven state machine implementation is messy




```
enum {ON, WAITING, OFF} state;

void eventhandler() {
  if(state == ON) {
    if(expired(timer)) {
      timer = t_sleep;
      if(!comm_complete()) {
        state = WAITING;
        wait_timer = t_wait_max;
      } else {
        radio_off();
        state = OFF;
      }
    }
  } else if(state == WAITING) {
    if(comm_complete() ||
       expired(wait_timer)) {
      state = OFF;
      radio_off();
    }
  } else if(state == OFF) {
    if(expired(timer)) {
      radio_on();
      state = ON;
      timer = t_awake;
    }
  }
}
```

Protothreads-based implementation is easier




```
int protothread(struct pt *pt) {
  PT_BEGIN(pt);
  while(1) {
    radio_on();
    timer = t_awake;
    PT_WAIT_UNTIL(pt, expired(timer));
    timer = t_sleep;
    if(!comm_complete()) {
      wait_timer = t_wait_max;
      PT_WAIT_UNTIL(pt, comm_complete()
                    || expired(wait_timer));
    }
    radio off();
    PT_WAIT_UNTIL(pt, expired(timer));
  }
  PT_END(pt);
}
```

- Code shorter than the event-driven version
- Mechanism evident from the code

Prothothread statements

```
int a_protothread(struct pt *pt) {
  PT_BEGIN(pt);
   /* … */
  PT_WAIT_UNTIL(pt, condition1);
   /* … */
  if(something) {
    /* … */
    PT_WAIT_UNTIL(pt, condition2);
    /* … */
  }

  PT_END(pt);
}
```

- PT_BEGIN( )
- PT_END( )
- PT_WAIT_UNTIL( )
- PT_YIELD( )
- PT_EXIT( )
- PT_SPAWN( )

Protothread scheduling

- The protothreads mechanism does not specify any specific method to invoke or schedule a protothread
- If a protothread is run on top of an underlying event-driven system, the protothread is scheduled whenever the event handler containing the protothread is invoked by the event scheduler

Prototype Implementation

- Proof-of-concept implementation in pure ANSI C
  - No changes to compiler
  - No architecture specific machine code
- Very simple implementation
- Very low memory overhead
  - Two bytes of RAM per protothread
  - No per-thread stacks

Example Implementation

```
struct pt { lc_t lc };
#define PT_WAITING 0
#define PT_EXITED  1
#define PT_ENDED   2
#define PT_INIT(pt)             LC_INIT(pt->lc)
#define PT_BEGIN(pt)            LC_RESUME(pt->lc)
#define PT_END(pt)              LC_END(pt->lc);    \
                                return PT_ENDED
#define PT_WAIT_UNTIL(pt, c)    LC_SET(pt->lc);    \
                                if(!(c))           \
                                  return PT_WAITING
#define PT_EXIT(pt)             return PT_EXITED
```

```
typedef void * lc_t;
#define LC_INIT(c)    c = NULL
#define LC_RESUME(c)  if(c) goto *c
#define LC_SET(c)     { __label__ r; r: c = &&r; }
#define LC_END(c)
```

Local continuations implemented with GCC labels-as-values C extension

```
typedef unsigned short lc_t;
#define LC_INIT(c)    c = 0
#define LC_RESUME(c)  switch(c) { case 0:
#define LC_SET(c)     c = __LINE__; case __LINE__:
#define LC_END(c)     }
```

Local continuations implemented with C switch statement

```
int sender(pt) {
  PT_BEGIN(pt);

  /* ... */
  do {

    PT_WAIT_UNTIL(pt,
                  cond1);

  } while(cond);
  /* ... */
  PT_END(pt);

}
```

```
int sender(pt) {
  switch(pt->lc) {
  case 0:
    /* ... */
    do {
      pt->lc = 8;
  case 8:
      if(!cond1)
      return PT_WAITING;
    } while(cond);
    /* ... */
  }
  return PT_ENDED;
}
```

Expanded C code with local continuations implemented with the C switch statement

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Memory overhead

- The prototype implementation needs to store local continuation for each protothread
  - 2 bytes in MSP430 and 3 bytes in AVR
- No per-thread stack

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Limitations of the prototype implementation

- Automatic variables are not saved across a blocking wait
  - User needs to save them explicitly before executing a wait statement
  - For functions that do not need to be reentrant, static local variables can be used instead of automatic variables
- C switch based implementation limits the use of the C switch statement together with protothreads statements
- A protothread cannot span across functions

Evaluation

- Authors rewrote seven event-driven state machine-based applications using protothreads
- Evaluation metrics
  - Reduction in code complexity
    - Number of explicit states
    - Number of explicit state transitions
    - LOC
  - Code footprint
  - Execution time

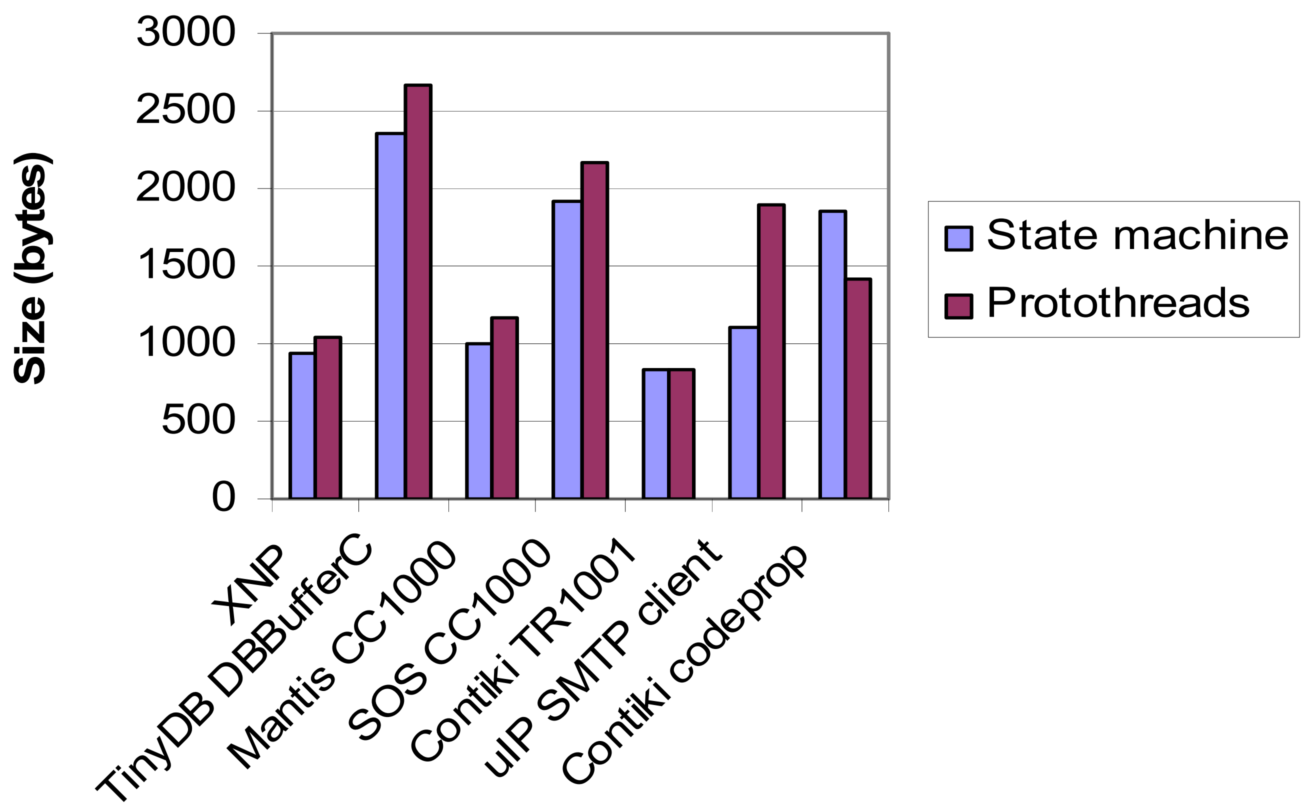
Reduction of complexity

	States before	States after	Transitions before	Transitions after	Reduction in lines of code
XNP	25	0	20	0	32%
TinyDB	23	0	24	0	24%
Mantis CC1000 driver	15	0	19	0	23%
SOS CC1000 driver	26	9	32	14	16%
Contiki TR1001 driver	12	3	22	3	49%
uIP SMTP client	10	0	10	0	45%
Contiki codeprop	6	4	11	3	29%

Protothreads completely eliminate or significantly reduce the state machine management problem. The source code is also significantly shortened.

Found state machine-related bugs in the Contiki TR1001 driver and the Contiki codeprop code when rewriting with protothreads

Code footprint



For these applications, code footprint increases by 200 bytes on average. The increase/decrease is dependent on the nature of the application. No conclusion can be drawn about the code footprint based on these examples.

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Machine code instruction overhead

	State machine	Proto-thread	Yielding protothread
MSP430	9	12	17
AVR	23	34	45

Protothreads incur very small machine code instruction overhead

Execution time overhead

	State machine	Protothreads, switch statement	Protothreads, computed gotos
gcc -Os	92	107	97
gcc –O1	91	103	94

Contiki TR1001 radio driver average execution time (CPU cycles)

Execution time overhead of protothreads is very low

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Conclusions

- Protothreads can reduce the complexity of event-driven programs by removing flow-control state machines
  - ~33% reduction in lines of code
- Memory requirements very low
  - Two bytes of RAM per protothread, no stacks
- Seems to be a slight code footprint increase (~ 200 bytes)
- Performance hit is small (~ 10 cycles)