Network Heartbeat in Linux

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Goal

- Synchronize all cluster nodes ticks
  - To implement a base component of Cluster Advanced Operating System (CAOS)
  - To improve HPC application performances
Cluster Advanced Operating System

Cluster Advanced Operating System (CAOS):
- Born from a System Programming Research Group’s idea
- A forthcoming *distributed operating system*

What’s new:
- **Synchronize ticks and tick’s related activities (timekeeping, process accounting, profiling, etc.)**
- Globally schedule: forcing all nodes in the cluster to perform in the same moment
  - Software timers related activities (*flush cache, etc.*)
  - System asynchronous activities (*page frame reclaiming, time sharing, etc.*)
- Offer additional features like *distributed data check-pointing, distributed debugging, process migration* etc.

Here we focus on the *Network Heartbeat* solution, which deals with the first point
Tick Synchronization

**Improve HPC application performance**

A possible solution is to force all nodes to perform system activities in a *synchronous* way, as shown in figure:

It’s not easy to achieve *global synchronization* of system activities for the whole cluster, in such a way to be sure that *all* nodes will execute the activities *exactly* in the same moment.

(a) co-scheduled OS noise
Why is not easy to achieve global synchronization of system activities?

- Each node uses his own timer device to measure time
- Even timer devices of the same type oscillate at slightly different frequencies
- Tick period is slightly different from node to node

Machines have different perception of the flow of time
Goal: To synchronize cluster’s nodes system activities

- We have to synchronize the flow of time among nodes
  - Network Time Protocol (NTP) is NOT a solution! It synchronizes only the Wall Clock Time...
  - We have to synchronize system ticks

- We need a general mechanism to schedule overall cluster’s system activities at the same future time

As a CAOS’s first implementation step, we introduce the Network Heartbeat, which allows tick synchronization.
Network Heartbeat Schema

(b) network heartbeat
Linux kernel offers specific abstract data structures to represent time related hardware devices:

- **struct clocksource**: provides a time value to the kernel
- **struct clock_event_device**: notifies the kernel that a *well defined amount* of time is elapsed
- **struct tick_device**: represents the best *clock event device* available to the kernel
Clocksource Device

The Linux kernel keeps track of the best available *clocksource* in the clock global variable

```c
struct clocksource {
    char *name;
    int rating;
    cycle_t (*read)(void);
    u32 mult, shift;
    unsigned long flags;
    cycle_t cycle_last;
    /* ... */
};
```

I.e. the `update_wall_time()` function updates *wall clock time* using the clock variable

```
offset = clock->read() - clock->cycle_last;
xt ime.tv_nsec += offset * clock->mult;
```
Clock Event Devices are used to raise hardware timer interrupts at specified time.

```c
struct clock_event_device {
    const char *name;
    unsigned long max_delta_ns,
        min_delta_ns;
    unsigned long mult, features;
    int shift, rating, irq;
    cpumask_t cpumask;
    int (*set_next_event)(unsigned long evt);
    void (*set_mode)(enum
        clock_event_mode_mode);
    void (*event_handler)();
    ktime_t next_event;
    /* ... */
};
```

The `clock event` data type is used to represent hardware like *LAPIC, HPET, DECREMENTER, etc.*

The function `set_next_event(msec)` is used to program the time of the next time event.
Tick Device

The Linux kernel keeps track of the best available *clock event device* in the `tick_cpu_device` per-CPU variable (*tick device* for short)

If *High Resolution Timers* are enabled:

- The *tick device* raises an hardware interrupt at the time of the next time event (not necessarily a tick time event)

```c
struct tick_device {
    struct clock_event_device *evtdev;
    enum tick_device_mode mode;
};
```

The *mode* field can be

- *periodic*: periodic tick mode
- *oneshot*: dynamic tick mode
The Network Heartbeat:

- Deals with the problem of the overall cluster’s nodes *tick synchronization*
- Patch for the Linux 2.6.24 kernel
- Designed for Symmetric-Multi-Processing (SMP) systems
- Developed for the *Intel IA32, Intel64* and *PowerPC64* architectures
- Based on the *Ethernet* communication channel
- Permits to dynamically change node’s tick frequency
The *Network Heartbeat Implementation* is built on two software components:

- **Network Event Device**: a *virtual* per-CPU timer event device, which replaces *local metronomes*

- **Nettick**: an interrupt *emulation* module, which translates the event "*new Ethernet frame*" in a *timer interrupt* event
The `nettick` module registers a new network protocol. It accomplishes the following:

- Recognize a new *Ethernet frame* type, introduced to notify the *tick* event type
- Send an *Inter Processor Interrupt* to all the online CPUs, thus “simulating” a local timer interrupt

The *Network Event Device* `net_event`:

- Handles the IPI sent by the `nettick` module and instructs the CPU on which is registered to execute tick and time management related functions
- Exports an *user interface* which allows users to choose the kernel operating mode (*global metronome* or *local metronomes*)
The virtual Network Event Device implements the `set_mode()` and `set_next_event()` methods

```c
static struct clock_event_device
    net_event = {
        .name = "net_event",
        .features = CLOCK_EVT_FEAT_ONESHOT,
        .set_mode = net_timer_setup,
        .set_next_event = net_next_event,
        .set_new_rate = set_new_rating,
        .event_handler = net_handlenoop,
        .rating = 0,
        .irq = -1,
        .nr_events = 0,
    };

DEFINE_PER_CPU(struct clock_event_device, net_events);
```

The (*event_handler)() will be re-associated to the right handler either when the device is registered or when rating changes.

The timekeeping framework’s interface was extended to make possible to change the rating value of a *clock event* device
The *nettick* module registers a new network protocol. As in example, on the *Intel x86* architecture:

```c
static struct packet_type
nettick_packet_type = {
   /* ETH_P_NETTICK 0x88CB */
   .type = htons(ETH_P_NETTICK),
   .func = nettick_rcv,
};
dev_add_pack(&nettick_packet_type);

nettick_rcv()
   send_ipi_mask(cpu_online_mask, NETTICK_TIMER_VECTOR);

N.B. the *smp_call_function()* function **cannot** be used because the nettick_rcv() handler is executed in *softirq* context!
```

The *nettick* protocol handler sends an Inter Processor Interrupt to all *online* CPUs.
Timer Interrupt Emulation

The new network protocol is required to make the implementation independent of the particular Network Interface Card’s driver.

- `nettick` handler is executed in *soft irq* context.
- `tick` related activities must be executed in *hard irq* context.
- IPI is the only way to interrupt other CPUs.
Timer Interrupt Emulation (2)

A new IPI message has to be registered by calling the `set_intr_gate()`.

- The IPI *network tick* message handler cleans the interrupt channel and then call the following function

```
local_nettick_timer_interrupt() {
    struct clock_event_device *dev =
        &__get_cpu_var(net_events);
    dev->nr_events++;
    dev->event_handler(dev);
}
```

1. *Gets* the ref. to the per-CPU *network event device*
2. *Increments* the device’s event counter
3. Enters the *timekeeping* system

- The chain of events is identical as the chain originated by a local timer interrupt!
Test Environment

Tests were performed on a 24-nodes Apple Xserve cluster, generously offered by Italian Defence’s General Stuff

- Each node is equipped with 2 dual core Intel Xeon 5150 processors (freq. 2.66GHz) overall 96 cores, 4GByte of RAM and 2 Gigabit Ethernet Network Interface Cards
- One of the 24 nodes was employed as master node
Tests goal: *overhead* and *scalability*

- NAS Parallel Benchmark - Embarrassing Parallel

(f) Benchmark EP Results
Network Heartbeat Test (2)

Tests goal: *overhead* and *scalability*

- NAS Parallel Benchmark - Embarrassing Parallel

(g) Benchmark EP Efficiency
The Network Heartbeat allows to synchronize cluster’s nodes ticks by means a *global metronome*

Tests highlight that proposed approach:

- *does not* introduce *overhead*

- *scales* adequately when cluster’s nodes increase in number

Future works:

- Extend *nettick* protocol to allow master node to schedule activities in a *centralized* way
Bibliography


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