

## Multi-task Real-time System Energy Consumption Minimization using Mini-Max Method

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### Introduction

Energy consumption reduction is a task of primary importance in embedded signal processing systems: sensor networks, mobile robots, wearable computers etc. [1]. Dynamic voltage scaling (DVS) is one of the most effective energy reduction technology [2,3,4,5,6]. Usually there are no or few problems if DVS is used in *soft real-times* system design or for task scheduling, where deadlines can be missed if the Quality of Service is kept [7,8,9]. It is different for *hard real-time* systems where is necessary to provide that the task never miss its deadline and the energy saving is maximized. The problems arise in *on-line* systems where the task execution time is unknown at the starting moment of the ordinary task. Therefore the best energy reduction regime can not be selected. In majority of investigations and publications this problem is solved analyzing periodic task executions with *off-line* determined execution times and determined priorities.

The author has proposed the method of on-line minimization for the hard task energy consumption in [10]. This method named *mini-max* is a DVS modification. The suitability investigation of this method for different single task realization regimes was developed in [11]. In this article the *mini-max* method suitability for multitask hard real-time systems with earliest-deadlines first (EDF) and rate-monotonic scheduling (RMS) was investigated and the results are presented.

### The *mini-max* method

By using the “*mini-max*” method deadline is guaranteed for the task execution at the minimal power till the critical time  $t_{cr}$ , after which the execution is finished at maximal clock frequency. It is special case of DVS where three different frequencies: nominal  $f_0$  (clock time  $\tau_{c0}$ ),  $f_{\min}(\tau_{c\max})$  and  $f_{\max}(\tau_{c\max})$ , are used. By compilation or simulation the task worst case execution time (WCET) is estimated.

The task on-line execution using the “*mini-max*” method:

- start at minimal  $f_{\min}$  frequency and minimal power consumption  $E_{\min}$

- test the current task step  $i$ , execution time  $t_{iran}$ :

$$t_{iran} \leq \tau_{c\max}(D - \tau_{c\min}N_{\max})/(\tau_{c\max} - \tau) = t_{crit} \quad (1)$$

If (1) satisfied and  $t_{iran} < t_{crit}$  the task execution is interrupted

$$E_{ci} = \tau_{c\max}P_{c\min}N_i, \quad (2)$$

else if  $t_{iran} = t_{crit}$  the task execution is continued until deadline D at maximal frequency  $f_{\max}$  and

$$E_{ci} = \tau_{cmix}P_{cman}(D - t_{crit}). \quad (3)$$

### Comparison off-line DVS and on-line *mini-max*

In hard real-time systems at the task starting time by using the classical DVS it is impossible to determine the best clock frequency for minimal power consumption and hard deadline conditions. Only after the task execution time estimation at compilation for every of task step the right frequency und  $\tau_{ci}$  can determined.

If the  $\tau_{ci} > \tau_{c\max}$  the power consumption for  $i$  task step is calculated using (2), else

$$E_{ci} = \tau_{ci}P_{ci}N_i. \quad (4)$$

The values  $\tau_{ci}$  and  $P_{ci}$  can be calculated analytically from  $P(f)$  or selected from table or graphical curve.

The gain from the *mini-max* method using energy consumptions in % can be estimated by using two characteristics  $\delta_{c0} = (E_{c0} - E_{m-m})100/E_{st}$  and  $\delta_{c0} = (E_{c0} - E_{m-m})100/E_{c0}$ . For the above example:  $\delta_{st} = 15\%$  and  $\delta_{c0} = 38\%$  [8].

### Multi task time driven system design methods

To estimate the possibility and the gain from the *mini-max* method using for multi task hard real-time

driven system there were two popular time driven task scheduling principles investigated earliest–deadlines first (EDF) or rate-monotonic scheduling (RMS). The conditions for  $n$  independent tasks with execution periods  $T_i = D_i$  and constant realization times  $WCET_i = C_i$  successful scheduling was proposed by Liu und Lyland [12].

For *RM* scheduling, where the task with shortest  $T_i$  has the highest priority, it is necessary to have utilization factor  $U$  less than  $U(n)$ :

$$C_1/T_1 + C_2/T_2 + \dots + C_n/T_n = U \leq U(n) = n(2^{1/n} - 1), \quad (5)$$

where  $U(n) = (2^{1/n} - 1) = 1$  when  $n = 1$ ,  $U(n) = 0.83$  when  $n = 2$ ,  $U(n) = 0.78$  when  $n = 3$ ,  $U(n) = 0.76$  when  $n = 4$ ,  $n \rightarrow U(n) \rightarrow \ln 2 \approx 0.693$ .

By using *RM* scheduling the highest priority tasks usually frequently interrupt other tasks and remarkable time can be consumed

For *EDF* scheduling, where the highest priority has the task which execution time is close by deadline or execution period  $T_i$ , utilization factor  $U$ :

$$C_1/T_1 + C_2/T_2 + \dots + C_n/T_n = U \leq 1. \quad (6)$$

### Multi task EDF with-on-line *mini-max* and off-line *DVS*

For multi task hard deadline real time system energy consumption gain estimation by using on-line *mini-max* and off-line *DVS* was performed. At first *EDF* scheduling was used and estimated. Example of three periodic tasks (Fig. 1) with  $T_j$  and  $C_j$  ( $C_1 = 3\text{ms}$  and  $T_1 = 8\text{ms}$ ;  $C_2 = 3\text{ms}$

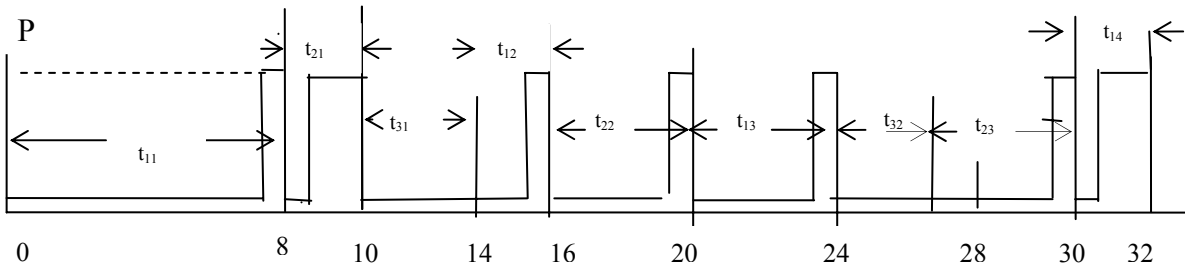
and  $T_2 = 10\text{ms}$ ;  $C_3 = 1\text{ms}$  and  $T_3 = 14\text{ms}$ ;  $U = 0.745$  was selected for analyses. The characteristics are selected according paper [13], where off-line *DVS* algorithm is used. Results of *mini-max EDF* scheduling are presented on Fig. 2 (scheduling for tasks with identical characteristics using off-line *DVS*).

### Multi task EDF with different execution times

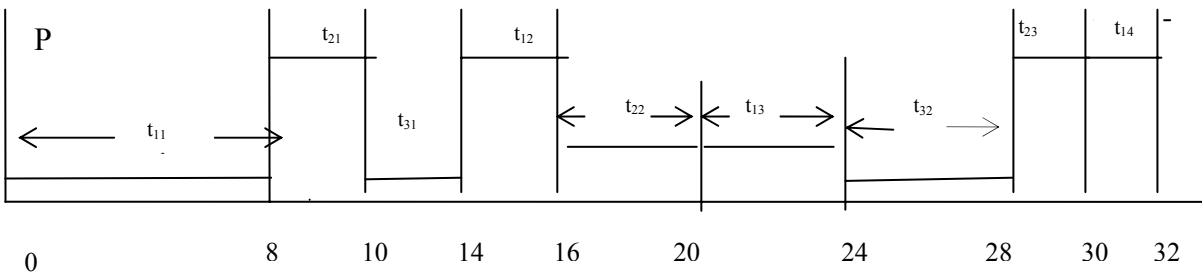
The previous section was devoted on-line and off-line *DVS* scheduling for *WCET*. Yet the main benefit from *mini-max* or *DVS* scheduling can be achieved at different execution time task scheduling. Using *EDF* algorithm for both scheduling the  $U \leq 1$  condition is necessary to satisfy. The results of energy consumption estimation for both scheduling at task execution time dynamic discrete changes are presented in Table 1 and Fig. 3.

**Table 1.** The results of energy consumption estimation

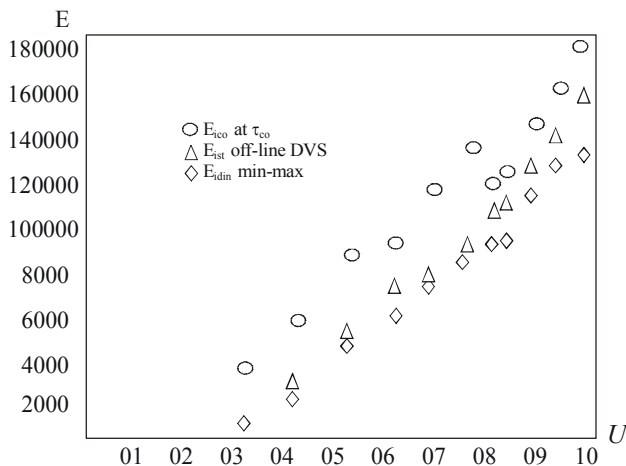
	tasks	U	$E_{m-m}$	$E_{dvs}$	$E_{\tau_{co}}$
1	3, 3, 1	0.75	92.9	98.9	104
2	1, 1, 1	0.30	13.5	13.5	54
3	2, 1, 1	0.42	27.4	31.5	78
4	2, 2, 1	0.52	49.0	54.0	96
5	2, 2, 2	0.59	61.7	79.0	108
6	3, 2, 1	0.65	74.3	80.4	120
7	3, 2, 3	0.80	93.0	110.4	126
8	3, 2, 4	0.86	99.6	115.0	156
9	3, 3, 3	0.89	117.8	126.4	162
10	3, 3, 4	0.96	130.3	150.4	174
11	3, 4, 3	0.99	129.0	160.0	180



**Fig. 1.** Time diagram for 3 task on-line EDF scheduling using mini-max



**Fig. 2.** Time diagram for 3 task off-line EDF scheduling using *DVS*. The energy consumption for the tree regimes:  $E_{m-m} = 92.9\mu\text{J}$ ,  $E_{DVS} = 98.4\mu\text{J}$  and  $E_{\tau_{co}} = 103.5\mu\text{J}$



**Fig. 3.** Energy consumption as function of utilization  $U$  for nominal frequency, off-line DVS and on-line mini-max

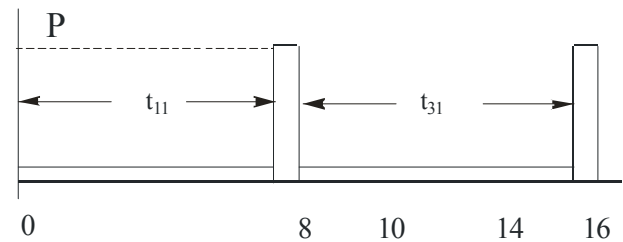
### Mini-max multi task RM scheduling

The problem of the mini-max for RM scheduling can be analyzed by using the previous simple example ( $C_1 = 3\text{ms}$  and  $T_1 = 8\text{ms}$ ;  $C_2 = 3\text{ms}$  and  $T_2 = 10\text{ms}$ ;  $C_3 = 1\text{ms}$  and  $T_3 = 14\text{ms}$ ;  $U = 0.745$ ). After finishing the highest priority

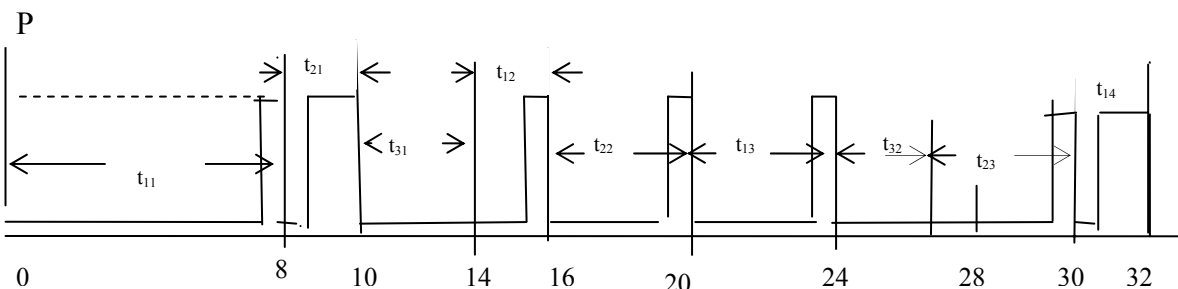
task with the smallest period  $T_1$  it is started again and no lower priority tasks can be executed (Fig.4).

To accommodate multi task RM for *mini-max* method the scheduling can be modified: after the task  $j$  execution in step  $i$  when deadline  $D_j$ , it can not be initiated again in spite of its priority  $p_k$  and freshed data.

Using *mini-max* method and modified RM scheduling for the same example the energy consumption time a diagram is built (Fig. 5). This time diagram of energy consumption is similar to the EDF scheduling diagram and the level of energy consumption is the same size for both.



**Fig. 4.** The mini-max RM scheduling problem



**Fig. 5.** Diagram for 3 task on-line modified RM scheduling using mini-max

### Conclusions

The analytic investigation confirms that *mini-max* method can be successfully used for energy consumption optimization in multi task systems:

1. For hard real-time multi task time driven EDF scheduling *mini-max* method at  $U \leq 1$  can be used on-line;
2. The energy consumption is linear to utilization factor  $U$ ;
3. The energy consumption using *mini-max* is roughly 10% smaller than using off-line DVS;
4. The *mini-max* method can be used for modified multi task RM scheduling and the benefits of energy consumption are similar to EDF scheduling.

Further experimental investigations are necessary for the method implementation.

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**A. Baums. Multi-task Real-time System Energy Consumption Minimization using Mini-Max Method // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 5(77). – P. 61–64.**

Applicability of mini-max method of scheduling for hard real-time multi task time driven EDF is investigated and the gain of its usage is estimated. The Multi- task scheduling can be implemented on-line using mini-max method. The energy consumption is roughly 10 % smaller for mini-max method compared to DVS off-line method. Mini-max method can be successfully used for modified multi task RM scheduling. Il. 5, bibl. 13 (in English; summaries in English, Russian and Lithuanian).

**A. Баумс. Использование метода Mini-Max для оптимизации энергопотребления в многозадачных системах реального времени // Электроника и электротехника. – Каунас: Технология, 2007. – № 5(77). – С. 61–64.**

Исследуются возможности использования метода mini-max для экономии энергопотребления в многозадачных системах реального времени. Основное внимание уделено системам реального времени с EDF планированием с критическими условиями. Показано, что метод mini-max открывает возможность в режиме „on-line” на 10 % понизить энергопотребление по сравнению с DVS off-line. Метод mini-max не может быть непосредственно применен при RM планировании многозадачных систем. Однако при использовании предложенного модифицированного RM могут быть получены аналогичные с EDF планированием результаты. Ил. 5, bibl. 13 (на английском языке; рефераты на английском, русском и литовском яз.).

**A. Baums. Minimakso metodo taikymas realaus laiko sistemų energijos suvartojimui minimizuoti // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 5(77). – P. 61–64.**

Nagrinėjamos minimakso metodo taikymo energijos suvartojimui minimizuoti realaus laiko daugelio užduočių sistemose galimybės. Daugiausia dėmesio skiriama realaus laiko sistemoms su EDF planavimu esant kritinėms sąlygoms. Parodyta, jog minimakso metodas įgalina realiu laiku iki 10 % sumažinti energijos suvartojimą palyginti su DVS metodu. Minimakso metodas negali būti tiesiogiai taikomas planuojant daugelio užduočių RM sistemas. Tačiau, taikant pasiūlytą modifikuotą RM, galima gauti tokius pat rezultatus kaip ir planuojant EDF. Il. 5, bibl. 13 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).