Chapter 57
DVFS Energy-Saving Scheduling of Navigation Receiver Based on Equilibrium Optimization

Wei Wu, Rui Ge, Shao-jie Ni and Fei-xue Wang

Abstract Hand-held or portable navigation receivers are powered by battery. The energy-saving design is very important to extend battery life. High-precision geodesic navigation receivers can be installed in fixed ground station. Dynamic-adaptive navigation receivers can be carried in a ship, aircraft, missile, or other vehicle. Although those carriers can supply sufficient power, low power design is of great benefit to system cooling, thus improves the receiver life cycle. Receiver processor can schedule task in busy or idle state. Dynamic Voltage and Frequency Scaling (DVFS) technology adjusts system voltage and frequency dynamically to make use of idle state, thus effectively saves system energy. This paper analyses the energy-saving scheduling design of multi-channel receivers, where the power consumption is remarkably reduced based on DVFS, meanwhile receiver works well in real-time. A DVFS energy-saving scheduling method based on equilibrium optimization is proposed, where the receiver clock frequency is dynamically adjusted corresponding to the number of satellites available using utilization equilibrium rule and its reverse counterpart. Our method optimizes the energy-saving factor based on utilization feedback approach and schedulability condition approach, and voltage and frequency adjusting is transformed into execution time increase. Monte Carlo simulations and experiment results show that our method is independent of scheduling algorithm and schedulability condition, and has low time complexity. Utilization equilibrium rule can obtain more balanced energy-saving factor compared with its reverse counterpart, and schedulability condition approach can acquire higher total utilization compared with utilization feedback approach, thus effectively reduce receiver power consumption.

Keywords Navigation receiver · Dynamic voltage and frequency scaling (DVFS) · Task scheduling · Energy-saving · Equilibrium optimization

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57.1 Introduction

For battery-powered hand-held or portable navigation receivers, the energy-saving design is very important to extend battery life. High-precision geodesic navigation receivers can be installed in fixed ground station. Dynamic-adaptive navigation receivers can be carried in a ship, aircraft, missile, or other vehicle. Although the carriers can supply sufficient power, low power design is of great benefit to system cooling, thus increases receiver life cycle. Modern embedded design widely uses Dynamic Voltage and Frequency Scaling (DVFS) technology, along with Dynamic Power Management (DPM) technology such as hibernate, sleep and shutdown, achieves system low-power design [1, 2].

Power optimization design of visible satellites' signal receiving is important for receiver energy-saving design. Literature [3] models DVFS power consumption based on low-power System on Chip (SoC), two scheduling approaches Cycle conserving EDF (CCEDF) and Look Ahead EDF (LAEDF) are applied to verify the power optimization. Literature [4] considers task preemptive scheduling in hard real-time system, uses multiple voltage levels for task set to obtain low power. Literature [5] illustrates that DVFS is suitable for thermal management, and is able to achieve a square or cubic reduction in power relative to the performance loss. Those known DVFS methods pay little attention to the task sets with dynamic timing parameters.

DPM configures processor into extreme low power mode, lets part/all of the circuit modules hibernate, sleep or shutdown, reduces the power consumption in system idle [1, 6]. The navigation tasks should always keep working, so that navigation receiver continually tracks the visible satellites. On the other hand, the user interface, such as LCD display and instruction control module, can operate under extreme low power mode when not used.

We propose a DVFS energy-saving scheduling method based on equilibrium optimization. The receiver working channel number is determined according to the visible navigation satellite number. Navigation task execution time optimization is achieved by adjusting voltage and frequency, and the optimal task working frequency is calculated. The power consumption of receiver processor is reduced as much as possible, meanwhile receiver works well in real-time.

57.2 Fundamentals and Modeling

57.2.1 DVFS Fundamentals

As for modern processor based on CMOS technology, the core power consumption can be composed of dynamic power and static power [3]:

$$P_{DD} = P_{Dynamic} + P_{static} \tag{57.1}$$

$$P_{Dynamic} = \alpha C_S V_{DD}^2 f_{clk} \tag{57.2}$$

$$P_{static} = I_{leak} V_{DD} \tag{57.3}$$

where α denotes activity factor, C_S denotes switching capacity, V_{DD} denotes core voltage, f_{clk} denotes clock frequency, I_{leak} denotes leakage current. The leakage current works at the level of mA or uA, so the dynamic power is ignored in our model.

Instruction cycles per unit time are calculated as:

$$n = f_{clk} t \tag{57.4}$$

With (57.2) and (57.4), the core energy per unit time is:

$$E_{DD} = \alpha C_S V_{DD}^2 n \tag{57.5}$$

When the core voltage is reduced, its power consumption achieves a square or cubic reduction. The core voltage should be higher than the threshold voltage of the transistor (when it starts conducting). In working region of CMOS circuits, clock frequency f_{clk} is approximately proportional to the core voltage V_{DD} [7]. As the supply voltage is reduced, working frequency also reduces, which is the fundamentals of DVFS technology. Meanwhile, frequency reduction increases the task execution time, which may influence the system real-time performance.

57.2.2 Receiver Task Analysis

Consider the navigation receiver with maximal M channels: Fig. 57.1.

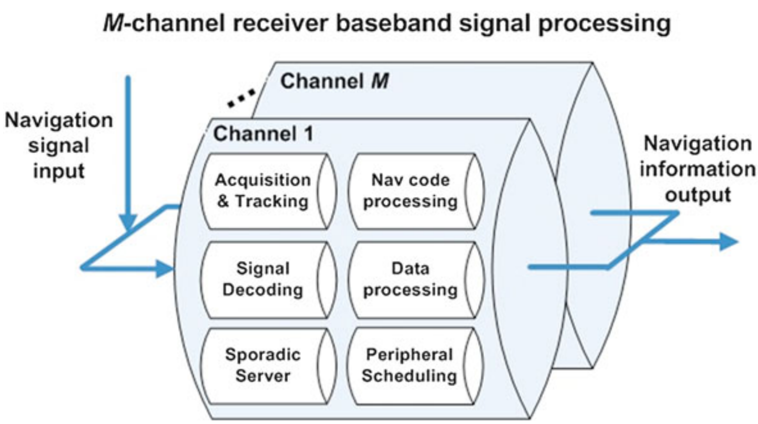

Fig. 57.1 Block of navigation receiver signal processing tasks

The receiver runs with m ($0 < m \leq M$) channels working, while the value of m can be dynamically adjusted according to the number of satellites available. Each working channel operates signal acquisition, tracking, decoding and processing tasks of the corresponding satellite.

57.2.3 Task Scheduling Modeling

Consider scheduling N periodic tasks. Task set is $T = \{\tau_1, \tau_2, \ldots, \tau_N\}$. Tasks can be modeled as

$$\tau_i = \{C_i, T_i, D_i\} \quad i = 1, 2, \ldots, N \tag{57.6}$$

where C_i denotes the worst-case execution time of τ_i. T_i denotes the period of τ_i. D_i denotes the relative deadline of τ_i. The utilization of τ_i is defined as:

$$U_i = C_i/T_i \qquad i = 1, 2, \ldots, N \tag{57.7}$$

In order to schedule receiver in the right way, parameters C_i, T_i and D_i need to be properly designed. The task set is schedulable if all tasks can achieve deadline without overhead. Assume $\boldsymbol{\Psi}$ denotes the scheduling algorithm. The period and deadline of receiver tasks are decided by system requirement, T_i and D_i are fixed parameters, so the scheduling algorithm of a receiver can be denoted as:

$$\boldsymbol{\Psi}\{\boldsymbol{T}\} = \boldsymbol{\Psi}\{C_i\}|_N \quad i = 1, 2, \ldots, N \tag{57.8}$$

57.2.4 DVFS Energy-Saving Scheduling

Consider m-channel working simultaneously. Using inter-task approaches [2], frequency reduction linearly increases task execution time. For a single channel, assume the worst case instruction cycles of task τ_i is denoted as n_i, the working frequency is f_i, than its WCET (Worst Case Execution Time) is n_i/f_i. thus the WCET of m-channel is:

$$C_i = mn_i/f_i \quad i = 1, 2, \ldots, N \tag{57.9}$$

Our goal is to minimize the system power consumption, meanwhile guarantee receiver task schedulable:

$$\textbf{Min} \qquad E_{DD} \tag{57.10}$$

$$\text{Subject to } \Psi\left\{\left(\frac{1}{f_i}\right)mn_i\right\}|_N \text{ schedulable}$$

57.3 Energy-Saving Algorithm

57.3.1 Energy-Saving Factor Optimization Based on Equilibrium

According to (57.10), m and n_i are already known, suitable f_i is the key of energy-saving scheduling. The energy-saving factor of task τ_i is defined as:

$$\eta_i = 1/f_i = Weight_i \eta_0 \quad i = 1, 2, \ldots, N \tag{57.11}$$

Different weighting schemes influence our chosen $Weight_i$. With utilization equilibrium rule, the obtained utilization is proportional to single-channel utilization, so the weighting factor is:

$$Weight_i \equiv 1 \tag{57.12}$$

With utilization reverse-equilibrium rule, the obtained utilization of each task is equal to 1/*N*, which is inversely proportional to single-channel utilization, so the weighting factor is:

$$Weight_i = \sum U_j / U_i \quad i = 1, 2, \ldots, N \tag{57.13}$$

57.3.2 Scheduling Based on Utilization Feedback Approach

When the scheduling algorithm $\boldsymbol{\Psi}$ is Rate Monotonic (RM) or Earliest Deadline First (EDF), the energy-saving factor can be calculated according to utilization. The upper bound of total utilization is denoted as $Bound_{\boldsymbol{\Psi}}$. For RM and EDF, we have [8]:

$$Bound_{RM} = N(2^{1/N} - 1) \tag{57.14}$$

$$Bound_{EDF} = 100\%$$

With (57.7), (57.9), (57.11) and (57.14), the energy-saving factor is:

$$\eta_0 = Bound_{\boldsymbol{\Psi}} / (\boldsymbol{Weight}. * \boldsymbol{U}) \tag{57.15}$$

where ***Weight*** denotes the $Weight_i$ vector, $\boldsymbol{U}$ denotes the U_i vector of *m*-channel task set.

57.3.3 Scheduling Based on Schedulability Condition Approach

As for reliability and real-time performance, receiver design adopts fixed priority scheduling, which is a Non-deterministic Polynomial (NP) problem [8]. Take the Katcher condition as an example, The schedulability condition of task τ_i is [9]:

$$\min_{0<t\leq D_i} W_i(t)/t \leq 1 \tag{57.16}$$

$$W_i(t) = \sum_{\tau_k \in hp(\tau_i)} \lceil t/T_k \rceil C_k + \sum_{\tau_l \in ip(\tau_i)} C_l$$

where $hp(\tau_i)$ denotes the set of tasks that have priorities higher than that of τ_i and $ip(\tau_i)$ denotes the set of tasks that have the priority the same as that of τ_i.

With (57.7), (57.9), (57.11) and (57.16), the energy-saving factor can be calculated. In order to improve the calculating efficiency of this NP problem, a dichotomy search method is used to search for energy-saving factor between the total utilization interval $[Bound_{RM,}\ 100\ \%]$. The search flowchart is Fig. 57.2:

Solving schedulability condition often takes much time. For on-line application, energy-saving factor η_0 can be pre-calculated off-line corresponding to different weighting rule and different value of $m(0 < m \leq M)$. Afterwards, η_0 can be obtained through look-up table as below Table 57.1:

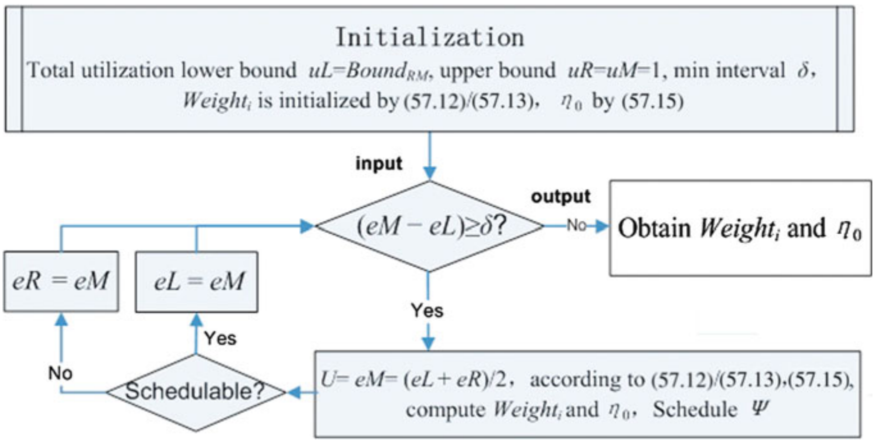

Fig. 57.2 Search flowchart of energy-saving factor

Table 57.1 Energy-saving factor look-up table

m	η_0 (Utilization equilibrium)	η_0 (Utilization reverse-equilibrium)
1	η_{01A}	η_{01B}
2	η_{02A}	η_{02B}
……	……	……
M	η_{0MA}	η_{0MB}

57.3.4 Task Working Frequency

With energy-saving factor calculated, the frequency for each task can be computed by (57.11):

$$f_i = 1/(Weight_i \eta_0) \tag{57.17}$$

Receiver design often chooses a base frequency f_0, the task working frequency can be any multiple of f_0. Assume task working frequency is between $[j_{min}f_0, j_{max}f_0]$, with positive integer $j_{min} < j_{max}$. The working frequency of each task can be calculated as:

$$f_i = \begin{cases} \lceil f_i/f_0 \rceil f_0 & j_{min}f_0 \le f_i \le j_{max}f_0 \\ j_{min}f_0 & f_i < j_{min}f_0 \\ j_{max}f_0 & f_i > j_{max}f_0 \end{cases} \tag{57.18}$$

57.4 Simulations and Experiments

57.4.1 Monte Carlo Simulation

Use Monte Carlo method simulates task set stochastically. The simulation parameters are:

1. task number N is from 2 to 20, with interval 2.
2. task period is randomly produced between [1, 1000] with uniform distribution.
3. task utilization is randomly produced between [0, 2/N] with uniform distribution.

For each N, produce 1,000 groups of task sets independently. Katcher condition and RM bound are used to obtain the optimal DVFS power consumption. Then, the average power of 1,000 groups of task sets for each N is calculated and plotted below (the normalized power for 100 % utilization is 1):

According to Fig. 57.3, the Katcher condition approach is better than the RM bound approach. Compared to RM bound, Katcher condition can obtain higher total utilization, thus reduce clock frequency more sharply. On the other hand, utilization equilibrium rule is better than its reverse counterpart. This is because

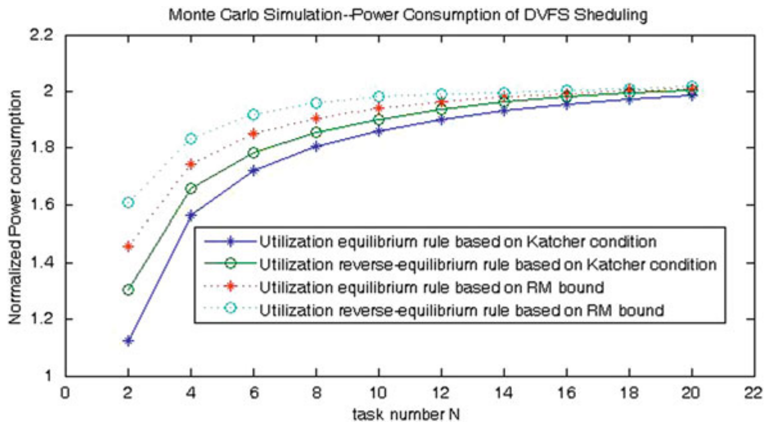

Fig. 57.3 Monte Carlo simulations of DVFS

utilization equilibrium makes frequency reduce proportionally for each task, and the energy-saving factor of each task is uniform. As for utilization reverse-equilibrium rule, the frequency reduction of each task results in disequilibrium. Some tasks may reduce more compared with utilization equilibrium rule, meanwhile some tasks may reduce much less, or even increase contrarily. That is why the utilization reverse-equilibrium rule consumes more power.

57.4.2 Adjust Clock Frequency According to Satellite Number

Certain receiver works at 400 MHz. Its normalized task parameters are as follows: Table 57.2.

With base frequency $f_0 = 10$ MHz, we examine the optimal power consumption corresponding to different channel number m. The Katcher condition is used with utilization equilibrium rule, with the value of m between [5, 12]. The optimal core power consumption with different m is as follows: Table 57.3.

Table 57.2 Task set parameters of a single channel in a receiver

i	Task name	Priority	C_i	$T_i = D_i$
1	Acquisition and tracking	3	51/1000	1
2	Signal decoding	2	57/1000	12
3	Data processing	2	354/1000	60
4	Sporadic server	2	18/1000	60
5	Navigation code processing	1	36/1000	108
6	Peripheral scheduling	1	33/1000	300

Table 57.3 Channel number m versus clock frequency and power

m	Core power	Working frequency (MHz)
5	P_0	200
6	$1.309P_0$	240
7	$1.633P_0$	280
8	$1.969P_0$	320
9	$2.314P_0$	360
10	$2.667P_0$	400
11	$3.025P_0$	440
12	$3.388P_0$	480

Note the power consumption with 5 channels working at 200 MHz is denoted as P_0

57.4.3 Power Consumption Analysis

Use look-up table with Katcher condition approach and utilization equilibrium rule, the energy-saving timing is analyzed below: Fig. 57.4.

In the above plot, figure (a) plots the number of satellites available versus time in 24 h, where the receiver working channel number is equal to the visible satellite number. Figure (b) plots the receiver working frequency versus time, which is proportional to the working channel number. Figure (c) plots the energy-saving factor versus time, which is inversely proportional to the working channel number. Figure (d) plots the instantaneous power consumption of the receiver. Compared with the receiver working at 400 MHz, our method saves about 23.6 % energy, and guarantee receiver schedulable even with 12 channels working.

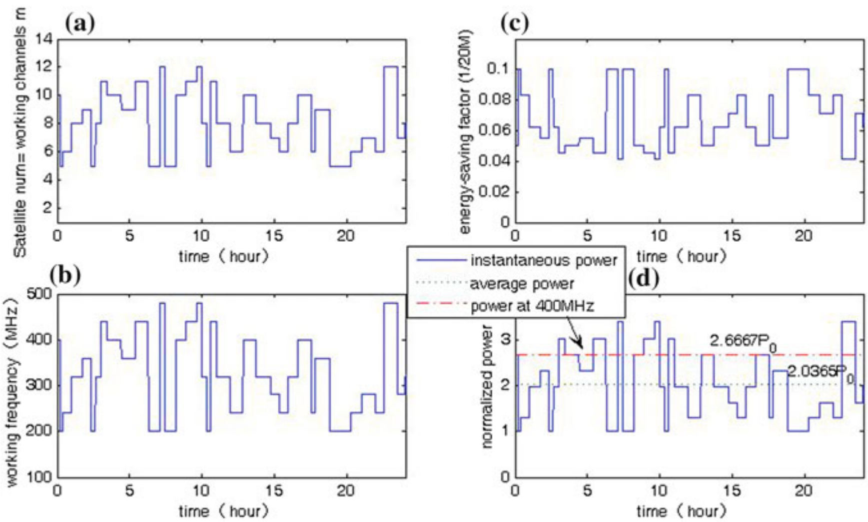

Fig. 57.4 Receiver energy-saving plot: (**a**) number of satellites available in 24 h; (**b**) frequency; (**c**) energy-saving factor; (**d**) core power

57.5 Conclusion

A DVFS energy-saving scheduling method is proposed based on equilibrium optimization. The receiver working channel number is determined according to visible navigation satellite number. Navigation task execution time optimization is achieved by adjusting voltage and frequency. Our method is independent of scheduling algorithm and schedulability condition, thus can extend to multi-channel real-time DVFS energy-saving design. Furthermore, utilization equilibrium optimization can be conveniently applied to both uniprocessor and multiprocessor energy-saving scheduling.

Simulation results show that our method has low time complexity, and can quickly calculate energy-saving factor suitable for receiver timing requirement. Utilization equilibrium rule can obtain more balanced energy-saving factor compared with its reverse counterpart, thus is more suitable for multi-channel receiver DVFS design, and reduces receiver power consumption more effectively.

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