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Using Chaos Theory based workload analysis to perform Dynamic Frequency Scaling on MPSoCs

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ABSTRACT

Embedded systems sometimes experience transient overloads due to workload bursts. Such systems have to be designed to take timely reactions at the occurrences of unexpected situations. The development of smart techniques that focus the available computing power on these urgent events and at the same time, slow down the processing frequency during inactive periods could be the key for preserving energy. In the context of this study, we present a Dynamic Frequency Scaling technique based on the workload trend of a dynamic wireless application. The system can adjust the operation frequency by analyzing the workload fluctuations without degrading the final performance or violating any deadlines. In this direction, we employ an abstract model of workload analysis that combines mathematical tools from the Chaos Theory field, allowing the dynamic handling of data streams with complex behavior. To evaluate the efficiency of the proposed approach we applied it using a real application workload on a cycle-accurate Network-on-Chip simulation framework. The simulation results showed that the proposed technique could achieve remarkable improvements at the final power consumption, between 17.5% and 37.8%, depending on the system constraints.

1. Introduction

In recent years, the mobile industry has developed so dramatically that has opened new challenges in the embedded system design domain. Embedded devices demand high performance under specific low power constrains. The development of proper methods that will extend the battery life, is without doubt an imperative need. Furthermore, embedded applications are time-constrained and their tasks must be completed before specific deadlines. In addition, embedded systems sometimes experience transient overloads due to hardware malfunctions or workload bursts. Such systems have to take timely reactions to the occurrences of unexpected usage scenarios. The development of smart techniques that focus the available computing power on these urgent events and, at the same time, slow down the processing during inactive periods could be the key for preserving energy at mobile devices.

Dynamic voltage and frequency scaling techniques [1] are commonly used to achieve significant power savings. These techniques can decrease the power consumption in processor elements by reducing the operation frequency. The majority of the embedded processors support configurations with these capabilities. Every processor frequency requires a minimum voltage supply for a stable system operation. Thus, the voltage supply defines the desired operation frequency. The correlation between operation frequency, voltage supply and power consumption is performed at the following equation:

$$P = CFV^2 + Pstatic \quad (1)$$

where P is the power consumption, C is the capacitance of the transistor gates, F is the operating frequency, V is the supply voltage and $Pstatic$ is the static power consumption.

As it is shown, the power consumption decreases quadratically with the voltage supply. It is obvious that the frequency scaling is directly associated with the voltage scaling. Dynamic Frequency Scaling (DFS) techniques can be used to adjust the processing frequency according to the system workload [2] in order to save the power consumption without degrading the system performance beyond the application tolerance. The open issue is how a system acts proactively at potential workload bursts.

The workload bursts are event driven situations. Unexpected transaction activations can cause transient overloads. In reality, these events are not completely random. An analysis can prove that behavioral patterns can exist. More precisely in the context of the current work we have developed an analytical methodology to identify these urgent events. The prediction of the dynamic

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workload trends is a very complex and resource consuming issue. The key point is the implementation of the time consuming calculations at design time keeping a flexible detection mechanism at run time [3]. This presupposes the analysis of representative workloads of real applications.

The aim of this study is to present a systematic way to predict potential transient overloads. In this direction, we employ a workload analysis methodology that combines mathematical tools from the Chaos Theory domain. The target is to handle dynamic data streams with complex behavior. More precisely, our approach extracts and predicts the "critical points" that represent the unstable situations of a wireless computing system. Efficient scheduling policies can be applied on these situations.

The rest of the paper is organized as follows. In Section 3, we start with a brief introduction at the Chaos Theory. An overview of the proposed methodology is presented in Section 4. The workload analysis techniques based on Chaos Theory are presented in Section 5, whereas the DFS methodology is presented in Section 6. We evaluate the proposed technique using a complex dynamic application on an NoC cycle-accurate simulator and the results are presented in Section 7. Finally, conclusions are drawn in Section 8.

2. Related work

The workload analysis has occupied literature since the early days of the computer science [4]. In recent years few researchers have proposed some new workload analysis methodologies [5–7] that are based on the construction of novel frameworks. This study [8] presents an analysis of system performance degradation induced by workload fluctuations. In [9], a workload model is presented that uses Markov chains for modeling job parameters. Some studies go even further by proposing adaptive techniques. In [10,11] a dynamic power management and a voltage/frequency scaling technique is correspondingly performed exploiting information about the workload trends. In [12], an approach is presented that defines the optimal CPU clock frequency under a fixed performance degradation constraint (of say 10%) based on dynamic program behavior. A energy aware DVFS technique where the workloads of the tasks are dynamically decomposed into on-chip and off-chip is also presented in [13]. Authors here [14] propose a run-time workload estimation technique for dynamic voltage scaling (DVS) even when the workload is highly non-stationary. Respectively, a DVS algorithm for scheduling real-time multimedia applications with dynamic workload characteristics, is presented in [15]. In this study [16] authors propose three DVS schemes for MPEG decoding based on a block level statistics prediction model. This work [17] presents a DVS algorithm for dynamic workloads of hard real-time systems, achieving an average energy saving about 15% over traditional DVS schemes.

The main contribution of the current study in respect with the aforementioned approaches is that for the first time a chaotic prediction model is implemented at the context of a DFS technique. The previous proposals have serious constraints to handle the design complexity. The critical issue is that the conventional analyses can achieve a workload prediction in respect with data that appears a discrete frequency spectrum. A discrete frequency spectrum appears a finite number of freedom degrees. This presupposes that the targeted workload has a periodical or semi-periodical behavior. The freedom degrees represent the number of the parameters that have to be taken into consideration to construct a prediction model. Correspondingly, if a workload has a continuous frequency spectrum, it will be required an infinite number of freedom degrees to construct a potential prediction. Thus, these techniques have limitations to define patterns for application workloads with these characteristics. The challenge is the fact that such cases are quite common at real dynamic applications and are considered as random or un-deterministic.

The proposed approach overcomes these limitations giving the possibility to predict these situations. The key point is that a continuous frequency spectrum can be occurred in two cases: (1) the first case behaves randomly with an infinite degrees of freedom that cannot be predicted and, (2) the second case behaves chaotically with a limited degrees of freedom that can be modeled. The current approach focuses on how it is possible to distinguish these situations. In this direction, a analytical methodology of 10 steps, is defined (Section 5) including prediction models that are exploited at the context of a DFS technique. To verify our methodology, a real application workload was analyzed achieving a power saving up to 37.8% (Section 6).

To summarize, the goal of our approach is to identify the critical points that represent the change phase of an embedded system operation applying power aware frequency scaling policies. The main contribution of our work is that we propose a systematic way to analyze real dynamic application workloads with ostensibly chaotic and non-ascertainable behavior. The novelty of our methodology is that we go a step forward of the aforementioned approaches providing new extensions including mathematical tools from the Chaos Theory field that are integrated in a complete frequency scaling technique.

3. Chaos Theory

Chaos Theory is a branch of mathematics, which studies the behavior of certain dynamical systems that may be highly sensitive to initial conditions. As a result of this sensitivity, the behavior of chaotic systems gives the impression that behave randomly. That is, tiny differences in the starting state of the system can lead to enormous differences in the state of the system even over fairly small timescales. This happens even though these systems are deterministic, meaning that their future dynamics are fully determined by their initial conditions with no random elements involved. This behavior is known as deterministic chaos, or simply chaos.

Chaotic behavior is also observed in natural systems, such as weather, earthquakes, human brain, magnetosphere. This may be explained by analysis of a chaotic mathematical model that represents such a system. Also, chaotic behavior has been observed in the laboratory in a variety of systems including electrical circuits, lasers, oscillating chemical reactions, fluid dynamics and mechanical and magneto-mechanical devices. Observations of chaotic behavior in nature include the dynamics of satellites in the solar system, the time evolution of the magnetic field of celestial bodies, population growth in ecology, the dynamics of the action potentials in neurons and molecular vibrations. Everyday examples of chaotic systems include weather and climate. There is some controversy over the existence of chaotic dynamics in plate tectonics and in economics. In a scenario where businesses operate in a turbulent, complex and unpredictable environment, the tenets of Chaos Theory can be extremely valuable.

To control chaos, the system or process of chaos has to be controlled. To control a system, the following are needed:

1. A target, objective or goal, which the system should reach. For a system with predictable behavior (deterministic) this may be a particular state of the system.
2. A system capable of reaching the target or goal.
3. Some means of influencing the system behavior. These are the control inputs (decisions, decision rules, or initial states).