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Performance of Self-Adapting Power-Saving Algorithms for ICT Systems

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Abstract—**As one of the large energy consumers worldwide, power consumption of network resources can be reduced significantly by dynamic activation/deactivation of resources depending on the current load or state of the system. In this paper, self-adapting algorithms are considered for such resources with/without activation overhead. ICT systems are modeled by a single/multi-server queuing system with finite buffer capacity whose control is performed by a Finite State Machine (FSM) with various hysteresis operation modes. Current system load is represented by the actual state of the ICT system resources, but the method is also applicable for actually measured or forecast load. Queuing systems are analyzed exactly under Markovian assumptions for which a new and efficient recursive algorithm is proposed yielding the probabilities of state and performance values as the mean delay, server activation/deactivation rates, as well as upper bound for the delay distributions. The proposed method allows for optimizing system parameters with respect to given thresholds for the mean delay and to delay percentiles.**

Index Terms: Power Saving, Resource Management, Self-Control, Queuing System, Activation Overhead.

I. INTRODUCTION

Increasing traffic demand in the internet, wireless and mobile communication systems, and in cloud data processing results in a tremendous power consumption. Today, the whole field of ICT is responsible for about 10 % of the whole energy consumption and the corresponding effects on the carbon footprint. Even with more efficient electronic and photonic technologies, the increase in power demand cannot be satisfied without massive power-saving operations. On the other hand, most communication links, routers and servers are operated at top speed, although their peak performance is only required sporadically and their average utilization amounts only to about 30 %.

For these reasons, many efforts are currently directed to power-saving operation modes as cloud computing, network virtualization, dynamic activation and deactivation of power-consuming resources, adaptive link rate aggregation and sleep modes, also known under the headline "Green ICT".

Methods for power saving in ICT systems have become a hot topic in the recent years, they range from the device level (on-chip power control), circuit level (low power circuit design), network level (transmission and coding, switching and routing, protocols) up to the application level (user behavior) and to system operation (power management, cooling). In this paper, we will focus mainly on the system level of ICT systems, specifically on communication network aspects, c.f. references [1-2] and references therein.

In a recent paper by the authors [1], the principal single hysteresis and a multiple serial hysteresis model have been analyzed analytically. In the contribution [2], a systematic classification of self-adapting algorithms for power-saving operation modes of ICT systems is suggested which includes measurement-based trends for advance server activations. Dual threshold policy is a common control strategy which has been applied, e.g., in overload control schemes for switching systems, flow control in communication protocols (e.g., TCP) and in power-saving algorithms for Adaptive Link Rate (ALR) strategy, c.f. [3]. This paper extends these results with respect to a more efficient multiple parallel hystereses model, delay distribution functions and the inclusion of activation overhead.

The rest of the paper is structured as follows: In Chapter II, a generic queuing model for dynamic activation/ deactivation is presented where the control is performed by a Finite State Machine (FSM). This model is applied to the parallel hystereses model which is the basis for the analysis of delay distributions. The model with parallel hysteresis is then extended to include activation overhead. In Chapter III, the parallel hystereses model is analyzed for Markovian arrival and service processes. In Chapter IV, numerical results for characteristic performance values are provided and discussed. Simulations are provided to study the influence of different arrival and service time characteristics. Finally, Chapter V summarizes the results and provides an outlook on ongoing further studies.

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II. MODELS FOR SERVER ACTIVATION/DEACTIVATION

A. Resource-Sharing Queueing Model

We consider a finite buffer queuing model with a total number of n servers and s buffer places for, e.g., data units ("Frames"), c.f. Figure 1. Arriving frames are directly served and occupy an available idle server; if all activated servers are occupied, the frame will be buffered and has to wait to become scheduled for service.

Arrivals may occur according to any type of arrival process (single or batch arrivals) with arrival rate λ. Service times at the servers may also be generally distributed with service rate μ (Markovian assumptions will be made, i.e., both interarrival times and service times are negative-exponentially distributed). Buffered frames will be organized on the basis of First-In, First-Out (FIFO) queuing strategy. As soon as a server becomes idle, it will be either immediately re-occupied by the frame waiting at the head of the queue or it will be deactivated. The state of the system is described by the vector (x,z), where x denotes the number of activated (busy) servers, and z denotes the actual number of buffered frames.

Activations and deactivations of servers as well as scheduling of buffered frames for service are controlled by a State Machine (Control). A free server may be activated instantaneously or only after an activation time with average $1/\alpha$, where α denotes the activation rate for an idle server. Below, we first consider one model without activation overhead (Section B); in Section C, the model is extended to include activation overhead.

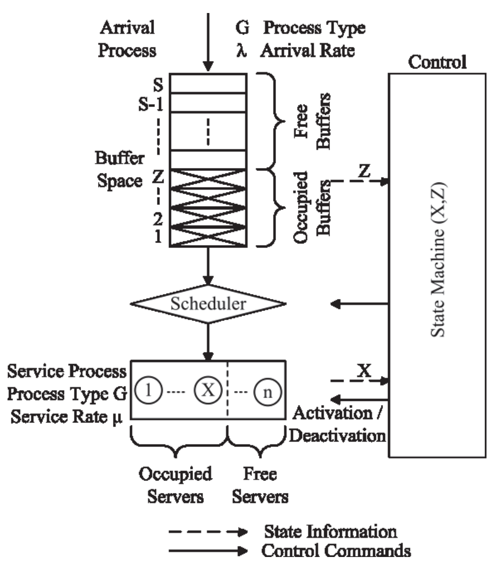

Fig. 1. Generic Model for Dynamic Activation/Deactivation of Servers
Parameters: n=total number of servers, s=total number of frame buffers
λ = arrival rate of frames, μ = service rate of a server

B. Multiple Parallel Hystereses Model

This model is an enhancement for the single hysteresis and multiple serial hystereses models previously discussed in [1] and [2]. It allows for adapting the number of active servers to the current system load by repeating the hystereses over all load values, and also allows for reduced delays by deactivating servers only when the system buffer becomes empty.

In Figure 2, a state transition diagram is shown where hysteresis is applied in parallel. Server activations occur at certain thresholds defined by the number of buffered frames in the system; namely $w^{(1)}$, $w^{(2)}$, $w^{(3)}$, $\ldots w^{(n-1)}$, where $w^{(i)}$ is the width of the i_{th} hysteresis. Deactivations of servers occur **only** at instants where a server becomes idle and when the buffer is empty. By this strategy, the service of buffered frames is maximally enforced which results in a reduction of frame delays.

C. Modeling Activation Overhead

In the previous model, it has been assumed that the activation of a "sleeping" server is immediate. In reality, activation overhead for, e.g., booting of a sleeping processor or resynchronization between distant communication link interfaces can be significant. In the following, we will assume that at each level x = 0, 1, …, n-1 the next server requires an activation overhead with average $1/\alpha$ before the activated server can start with the service, c.f. Figure 3. Note that in Figure 3, the levels $w^{(i)}$ of buffered frames for the initiation of the next server activation have been maintained as in the model without activation overhead, i = 0, 1, 2, …, n-1 (this can, of course, be defined freely). For the mathematical analysis, it will be assumed that the activation durations are also negative-exponentially distributed with termination rate α.

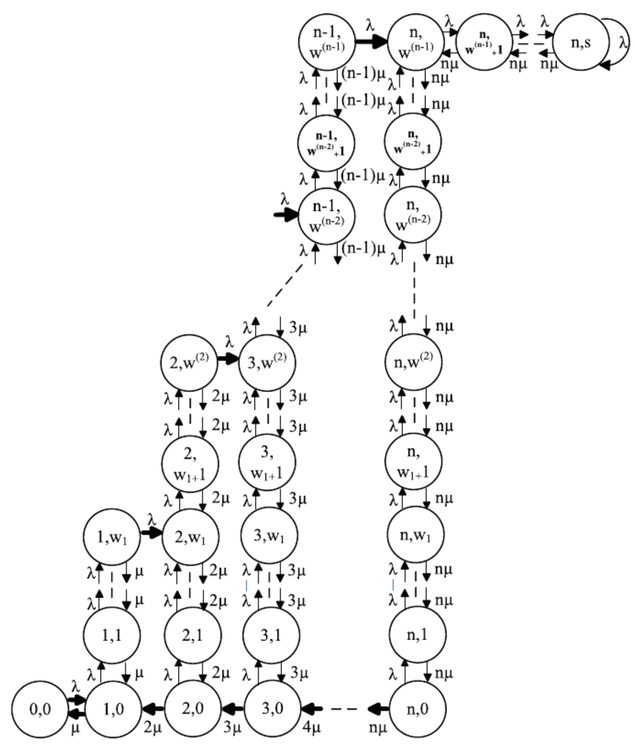

Fig. 2. State Transition Diagram for the Multiple Parallel Hystereses Model

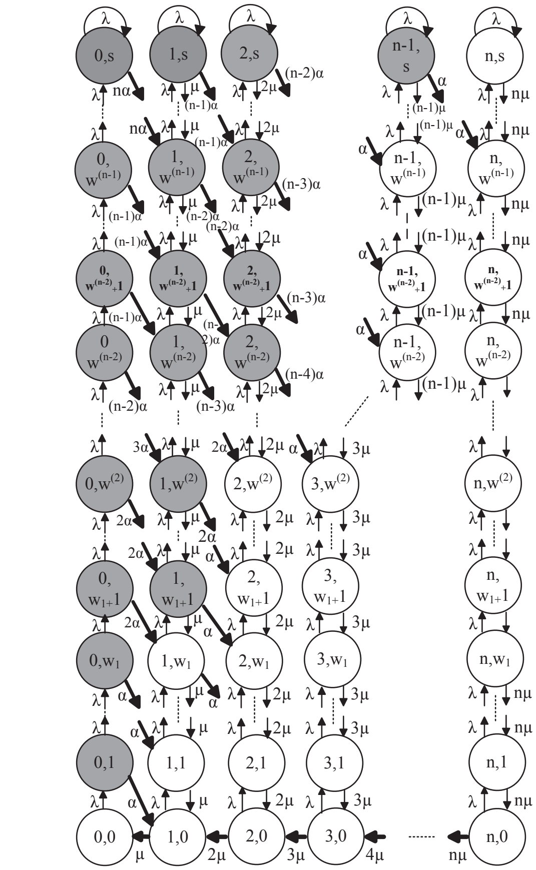

Fig. 3. State Transition Diagram for the Multiple Parallel Hysteresis Model with Activation Overhead

III. MATHEMATICAL ANALYSIS OF POWER-SAVING ALGORITHMS

A. Theoretical Background

For Markovian queuing models with hysteresis thresholds, many specific application cases have appeared in the literature. For the single hysteresis model, P. Tran-Gia [4] derived closed-form expressions for the probabilities of state by a method of macro-state aggregation. The most generalized models have appeared in two seminal and fundamental contributions by O.C. Ibe and J. Keilson [5] and by J.C.S. Liu and L. Golubchik [6]. The analysis of [5] is based on the method of Green's function, while the analysis approach of [6] overcomes limiting effects by applying stochastic complementation method; they discovered also extensions to bulk arrivals.

Although both approaches in [5,6] arrived at closed form results, their numerical evaluation is anything but simple due to transform expressions with singularities. In our paper [1], we have described a simple 13-step recursion algorithm for the steady-state probability distribution p(x,z) of the single hysteresis model from which all relevant performance metrics are derived. The recursive property is also maintained for the parallel hysteresis model.

B. Performance of the Multiple Parallel Hysteresis Model

The probabilities of state for the state transition diagram of Figure 2 follow according to a slightly modified recursive algorithm:

- Assume p(0,0) as a parameter (p(0,0)=1)
- Express p(1,0) from balance equation for state (0,0)
- Assume $p(1,w^{(x)})$ as a parameter with x=1
- Solve p(1,j) from balance equations for states for states (1,j+1), j=w_1-1,…,0
- Solve $p(1,w^{(1)})$ by equating expressions for p(1,0)
- Express p(1,j), j=w_1-1,…,1 as function of p(0,0)
- Solve p(2,0) from balance equation for state (1,0)
- Repeat the last 5 steps for x=2,3,…,n-1
- Solve p(n,j) from balance equations for states (n,j-1), j=1,…,$w^{(n-1)}$
- Solve $p(n,w^{(n-1)}+j)$ from balance equations for states $(n,w^{(n-1)}+j-1)$, j=1,2,…,s-$w^{(n-1)}$
- Find p(0,0) from the normalization condition
- Multiply with p(0,0) to find all state probabilities by multiplying with p(0,0)

From the stationary probabilities of state p(x,z), the most important performance metrics can be derived for any threshold x=1,2,..,n-1. Metrics for this model can be easily obtained by slightly modifying those mentioned and explained in **Error! Reference source not found.** and **Error! Reference source not found.**. Below we only explain two new metrics:

- Upper bound of the mean waiting time of arriving frames (1)

$$E[T_w]^* = \sum_{z=0}^{s-1} p(x,z)\left[\frac{1}{\alpha}+\frac{z}{\mu}\right] + \sum_{x=1}^{n}\sum_{z=0}^{s-1} p(x,z)\frac{z+1}{x\mu}$$

- Compl. delay DF of buffered frames (based on upper bound) (2)

$$\frac{W(>t)}{W} = \sum_{z=0}^{s-1} p(0,z).[M(\alpha) \otimes \mathrm{E}_z(\mu)]^c + \sum_{x=1}^{n}\sum_{z=0}^{s-1} p(x,z).E_{k+1}^c(x\mu)$$

where M(α) and E_Z(μ) denote the distribution functions for an M- and an Erlang-order z-phase, respectively. The symbol ⊗ denotes the convolution operation of the corresponding probability density functions.

Equations (1) and (2) represent an upper bound of the mean waiting time of arriving frames and the complementary distribution function of buffered frames based on the upper bound approximation. For the upper bound it is assumed that server activations which occur during the waiting process of a "test customer" will not increase the service rate, i.e., the delay DF can be approximated by the workload which has been met by the test customer on its arrival.

IV. EXAMPLE CASES

A. Multiple Parallel Hysteresis Model

Figs. 1a-c) show the results for the server state distribution, the mean waiting time of buffered frames, and the server activation/deactivation rate dependent on the load factor ρ for n = 10 servers, s = 100 buffers and for the hysteresis width w_i = 1, 3, and 5. The results show an almost constant average delay and low server activation/deactivation rates. In Figure 6d), an example is shown for the upper bound of the delay distribution function of delayed frames for w_i = 3 for the load factors ρ = 3, 6 and 9. Delay distributions show a highly hypoexponential characteristic.

Figure 1e) provides simulation results for this model for four different interarrival time characteristics D, M, H_2 with c_A = 2, and c_A = 5, where c_A denotes the coefficient of variation. The arrival process has only effects on the mean waiting times, but the positive effect of reduced values over a large range of the load factor is maintained. Fig. 1e) shows Markov arrivals and a realistic 3-modal service time DF modeled according to internet packet length distributions; the new packet length distribution shows almost no effect on the delays compared to the negative-exponential distribution.

Figures 2a,b) refer to the same model parameters as before but with server activation overhead. Fig. 2a) shows results on the mean waiting time of buffered frames and on the server activation rate dependent on four different values of the width factor w for the ration α/μ=0.5. Except for a slight increase, the mean delays have similar shapes as in case without activation overhead. The increase of delays is contrasted with the strong decrease of the server activation rate with increasing width w. The effect of overhead is demonstrated in Fig. 2b). Increasing overhead has to be paid by increasing delays; however, the positive effect of being largely insensitive wrt the load factor is still maintained.

V. CONCLUSIONS

In this study, we have shown that dynamic server activations/deactivations are a proper method for power reduction and that the Finite State Machine (FSM) model, represented by its state transition diagram, can be used to control the server/buffer system. The multiple hysteresis models adapt automatically to the actual load. Frequent oscillations of server activations/deactivations can largely be reduced and parameters can be optimized with respect to prescribed bounds on the additional delay or delay percentiles caused by the power-saving algorithms. Specifically advantageous performance characteristics have been achieved with the new multiple parallel hystereses model with respect to robustness of mean delays with respect to the load factor and with respect to low percentiles of the delay distribution functions. It has been shown by simulations that these properties are maintained also for a wide range of non-exponential interarrival time and realistic service time characteristics. Finally, the hysteresis model has been extended to include server activation overheads for, e.g., boot times or re-synchronization times which can still be analyzed by the recursion method.

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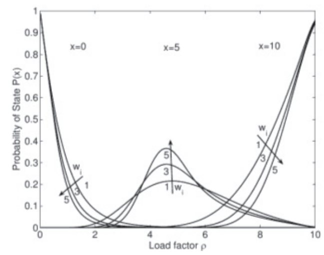

Fig. 1a. Probability of x Active Servers versus Load Factor ρ

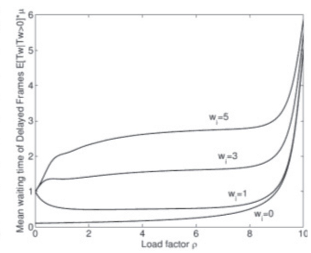

Fig. 1b. Mean Waiting time of Delayed Frames E[TwITw>0]*μ Versus Load Factor ρ

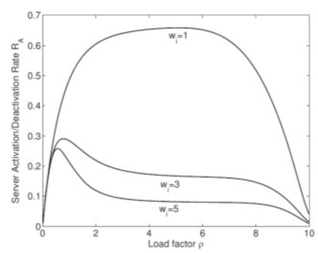

Fig. 1c. Server Activation Rate versus Load Factor ρ

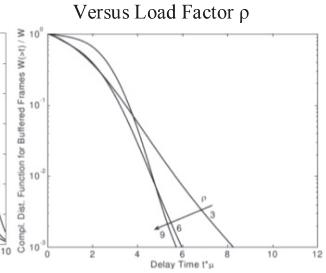

Fig. 1d. Comp. Distribution Function for Waiting Times of Buffered Frames

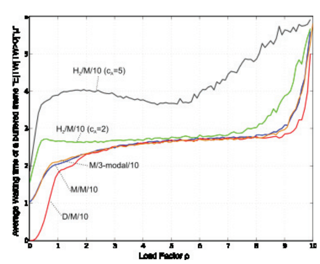

Fig. 1e. Simulation Results:Influence of Interarrival Time and Realistic Service Time DF

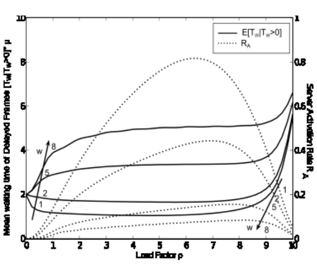

Fig. 2a. Mean Waiting time of Delayed Frames and Server Activation rate versus Load ρ

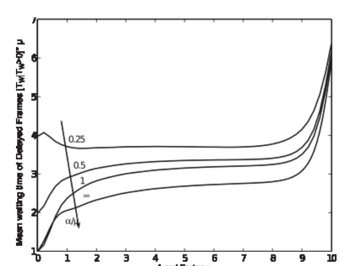

Fig. 2b. Different Overhead Loads versus Load Factor ρ