SOME PERFORMANCE ANALYSIS APPLICATIONS OF STOCHASTIC MODELING

Ph.D. Dissertation Summary

by

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1 Motivations and Purposes

Models have been used for a long time to understand and analyze processes, which try to capture the essence of problems, and – as far as possible – simply describe the operation of these processes.

In this work, we deal with two main topics. First, we investigate the spreading of services (applications), model the spreading process, and evaluate the models. These models offer an alternative approach for the application providers to spread an application exploiting the direct communication between the users. Besides, we show that our applied modeling techniques can be used in the wood industry, too, by determining the bottleneck of the wooden window manufacturing process using a deterministic and stochastic Petri net (DSPN) model.

Then, we propose a model for opportunistic spectrum access and analyze its effects. In opportunistic spectrum access, service providers can opportunistically use each other's unutilized frequency bands. Our goal is to show that using our model, the service quality improves, while the service providers can realize an extra profit.

The goals can be summarized as follows:

- modeling application spreading in mobile ad hoc environments [1, 2, 3, 4, 5, 6, 7],
- showing that the applied modeling techniques can be used also in the wood industry,
- modeling opportunistic spectrum renting in mobile cellular networks [8, 9, 10].

2 Research Methodology

This section provides the short overview of methodology applied to solve the problems covered in the dissertation. Performance evaluation can be carried out by either using a simulation program, or by mathematical analysis with numerical procedures, or build the system and then measure its performance [16]. Although simulation allows us to construct more sophisticated models, mathematical analysis generally needs lower computational effort [17].

Investigating application spreading in mobile ad hoc environments is a novel research field. However, the methodology used in this area contains well-known elements.

Queuing networks are used for modeling systems, which can be considered as a set of interacting services. In this area, many results were obtained in the last century, such as the Jackson networks [18], for which an efficient product-form solution exists; and the mean value analysis [19], by which the analytical solution of closed queuing networks (CQNs) [20] can be obtained. In our application spreading models, the user population is finite. Therefore, using CQNs to obtain the behavior of our system is an obvious idea. However, the acyclicity of our model does not allow the use of the mentioned traditional processes (namely, if a user purchases an application, he will never lose it again).

On the other hand, there exist high-level modeling techniques such as stochastic Petri nets [21], which are also commonly used in this area. The standard approach for analyzing SPNs is to construct the continuous-time Markov chain (CTMC) corresponding to the underlying stochastic behavior of the SPN [22] and perform the steady state or transient analysis analytically [23] or by simulation. However, this approach becomes unfeasible due to the size of the state space if we consider a network composed of a large number of components. In this dissertation, we describe the mean field approach, which is a fluid approximation method for model evaluation. Applying this method, the analysis will terminate within a few seconds, even when the state space explodes due to the high number of tokens. This method is based on [24], while we present it in a form that is directly related to the applied definition of SPN [5]. Besides, we provide a formal relation between the CTMC and its fluid approximation, too.

Unfortunately, the use of inhibitor arcs violates the density dependent property in the underlying CTMC of the SPN. Therefore, the fluid approximation method is not feasible in these cases. Instead, simulation can be used to evaluate the model. The simulation of stochastic Petri nets is supported by many known tools, like the ones presented in [25, 26, 27].

In a manufacturing process, the work phases have deterministic delay. A process, in which the delays of the transitions are either exponentially, or deterministically distributed, can be appropriately described by a DSPN [28]. DSPNs are similar to SPNs, except that deterministically delayed transitions are also allowed in the Petri Net model. However, DSPNs have greater modeling strength than SPNs, there are some restrictions in the model evaluation phase. Although it has been shown [29, 30, 31] that in some special cases, a DSPN can be analyzed even with concurrently enabled deterministic transitions, analytical solution using the underlying stochastic behavior can generally be obtained only if there is only one enabled deterministic transition in each marking [28]. In our case, simulation must be used to get the steady state or the transient solution of the DSPN.

In our other topic, we investigate the opportunistic spectrum renting in mobile cellular networks using a queuing model. It is worth emphasizing that some queuing models for spectrum renting were already worked out [32, 33, 34]. However, they could not be directly applied to the present proposal. In this work, the analytical solution of our model is described, while additional results are presented via simulation.

3 New Results

The achieved results can be categorized into two groups of theses.

Thesis 1: Two Performance Analysis Applications Based on Deterministic and Stochastic Petri Net Models [1, 2, 3, 4, 5, 6, 7]:

We elaborated a CQN and two SPN models for application spreading in mobile ad hoc environments. In the evaluation of these models, different techniques were used depending on the complexity of the models. Moreover, we modeled the wooden window manufacturing process with DSPN to demonstrate that the stochastic models can be applied in the wood industry (Chapter 2 of the dissertation).

The own contributions are summarized as follows:

- *Thesis 1.1: We proposed a CQN model which can be simply used for giving an analytical lower and upper bounds on the number of application purchases (Subsection 3.1.4).*

- *Thesis 1.2: We demonstrated that the mean field based methodology can be applied for obtaining the transient solution of a SPN, if the underlying Markov chain of the SPN is density dependent (Subsection 3.1.5).*

- *Thesis 1.3: We applied the mean field based methodology for obtaining the transient solution of our basic SPN model, and we gave an analytical approximation* *on the number of application purchases in the order of seconds. (Subsection 3.1.5).*

- *Thesis 1.4: We proposed an extended version of the basic SPN model, for which the main properties of the application spreading process can be determined by running transient simulation (Subsection 2.1.4).*

- *Thesis 1.5: Using a DSPN model, we identified the bottleneck of the wooden window production process and determined the measure of the extension for eliminating the main bottleneck (Section 2.2).*

Thesis 2: Modeling Opportunistic Spectrum Access in Mobile Cellular Networks [8, 9, 10]:

We proposed a spectrum sharing model, in which the service providers opportunistically use each other's unutilized frequency bands. We showed that using our opportunistic spectrum access model, the service quality improves, while the service providers can realize an extra profit (Chapter 3 of the dissertation).

The specific contributions are summarized as follows:

- *Thesis 2.1: We elaborated a spectrum sharing policy based on the idea of opportunistic spectrum access. In the model, a high level of cooperation is realized between the mobile service providers. Besides, the model considers the current technical constraints, too, which were ignored by most of the related works (Subsection 3.2.2).*

- *Thesis 2.2: We demonstrated via simulations that the service quality can be improved applying the elaborated spectrum sharing policy. Moreover, we also demonstrated that the cooperating parties can realize more profit using our model than in the current environment (Section 3.3).*

- *Thesis 2.3: We elaborated the mathematical model of the above mentioned spectrum sharing policy. We used a two-dimensional CTMC to get the numerical results of the model. Since the results correspond to the simulation results, the Markovian mathematical model can be considered as a good approximation of the original model, where the channel holding times and the interarrival times are log-normally distributed (Subsections 3.2.3 and 3.3.1).*

- *Thesis 2.4: We identified and measured the main drawback of our model, the forced termination phenomenon. In a heavily loaded system, the forced termination increases to a level that is annoying for the mobil subscribers. To handle this problem, we elaborated a method for the protection of the ongoing calls based on the Adaptive Random Early Detection (ARED) rule (Subsection 3.3.3).*

4 Application of the Results

In the first thesis group, we mainly deal with application spreading in mobile ad hoc environments. The results show an alternative approach for mobile service providers, and can initiate a new direction for the further exploration of this aspect of ad hoc networks.

Moreover, we applied a mean field based methodology for stochastic Petri nets. With this fluid approximation method, the analytical approximation of stochastic Petri nets can be obtained within a few seconds, since the complexity of the solution is linearly proportional with the number of places in the Petri net.

In the first thesis group, we also showed the possible application of stochastic modeling in the wood industry. The results can be directly applied for those companies which want to increase their productivity: the bottleneck of the production process can be determined with the model. Moreover, the model helps determine the necessary measure of the expansion, too.

In the second thesis group, we set up an analytical model for opportunistic spectrum access, which is useful for the performance evaluation of spectrum renting. We showed that the opportunistic renting of frequency bands improved the main performance indices. To alleviate the main drawback of our scheme, we proposed a call admission control process. We showed that using this process, the blocking probability and the forced termination probability can be balanced. Moreover, we showed that both cooperating parties can realize an extra profit using our model, even if no discount is offered for the tenant operator.

Own Publications Related to the Dissertation

[1] Á. Horváth, "Modeling opportunistic application spreading," in *Proceedings of the Second International Workshop on Mobile Opportunistic Networking*, pp. 207–208, ACM, 2010.

[2] Á. Horváth and K. Farkas, "Alkalmazsok terjedsnek vizsglata mobil ad hoc hlzatokban," in *Proceedings of IKT2010, Dunaújváros, Hungary*, pp. 1–6, 2010.

[3] Á. Horváth and K. Farkas, "Modeling self-organized application spreading," in *Access Networks*, pp. 71–80, Springer, 2011.

[4] Á. Horváth and K. Farkas, "Modeling application spreading using mobile ad hoc networks," in *Wireless and Mobile Networking Conference (WMNC), 2010 Third Joint IFIP*, pp. 1–6, IEEE, 2010.

[5] M. Beccuti, M. De Pierro, A. Horváth, Á. Horváth, and K. Farkas, "A mean field based methodology for modeling mobility in ad hoc networks," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, pp. 1–5, IEEE, 2011. **Number of independent citations: 2**.

[6] Á. Horváth and K. Farkas, "Techniques for modeling mobile application spreading," *Infocommunications Journal*, vol. IV, no. 1, pp. 13–20, 2012.

[7] Á. Horváth, "Usability of deterministic and stochastic Petri nets in the wood industry: a case study," *In Proceedings of the* 2^{nd} *International Conference on Computer Science, Applied Mathematics and Applications (ICCSAMA 2014)*, pp. 119–127, 2014.

[8] J. Boros and Á. Horváth, "GSM szolgáltatók közötti együttműködés vizsgálata," in *Proceedings of OGIK 2012.*, 2012.

[9] Á. Horváth, "Applying opportunistic spectrum access in mobile cellular networks," *Infocommunications Journal*, vol. V, no. 2, pp. 36–40, 2013.

[10] T. V. Do, N. H. Do, Á. Horváth, and J. Wang, "Modelling opportunistic spectrum renting in mobile cellular networks," *Submitted to Elsevier Journal of Network and Computer Applications*, 2013.

Other Own Publications

[11] T. Bérczes and Á. Horváth, "A finite-source queuing model for spectrum renting in mobile cellular networks," in *Accepted in Proceedings of the 10th International Conference Elektro 2014, Rajecké Teplice, Slovakia*, 2014.

[12] P. Schaffer, K. Farkas, Á. Horváth, T. Holczer, and L. Buttyán, "Secure and reliable clustering in wireless sensor networks: A critical survey," *Computer Networks*, vol. 56, no. 11, pp. 2726–2741, 2012. **Number of independent citations: 10**.

[13] J. Boros, Á. Horváth, and L. Jereb, "Szűk keresztmetszetek feltárása többrétegű architektúrákban," in *Proceedings of IF2011, Debrecen, Hungary*, pp. 758–765, 2011.

[14] L. Bacsárdi and Á. Horváth, "Mobile ad hoc networks in the applied informatics," *GP (Journal of Scientific Society of Mechanical Engineering, Hungary)*, vol. 61, no. 1-2, pp. 25–27, 2010.

[15] Á. Horváth and T. Kárász, "A konszolidáció hatása az igények rendelkezésre állására," in *Student Conference organized by BME and HTE, Budapest, Hungary*, pp. 1–4, 2007.

Bibliography

[16] L. Kleinrock, "On the modeling and analysis of computer networks," *Proceedings of the IEEE*, vol. 81, no. 8, pp. 1179–1191, 1993.

[17] T. V. Do and R. Chakka, "Simulation and analytical approaches for estimating the performability of a multicast address dynamic allocation mechanism.," *Simulation Modelling Practice and Theory*, vol. 18, no. 7, pp. 971–983, 2010.

[18] J. R. Jackson, "Networks of waiting lines," *Operations Research*, vol. 5, no. 4, pp. 518–521, 1957.

[19] M. Reiser and S. S. Lavenberg, "Mean-value analysis of closed multichain queuing networks," *Journal of the ACM (JACM)*, vol. 27, no. 2, pp. 313–322, 1980.

[20] T. G. Robertazzi, *Computer Networks and System: Queueing Theory and Performance Evaluation.* Springer, 2000.

[21] M. A. Marsan, G. Balbo, G. Conte, S. Donatelli, and G. Franceschinis, *Modelling with Generalized Stochastic Petri Nets.* John Wiley and Sons, 1995.

[22] G. Yin and Q. Zhang, *Continuous-time Markov chains and applications.* Springer New York, 1998.

[23] W. J. Stewart, *Introduction to the numerical solution of Markov chains*, vol. 41. Princeton University Press Princeton, 1994.

[24] T. G. Kurtz, "Solutions of ordinary differential equations as limits of pure jump markov processes," *Journal of Applied Probability*, vol. 7, no. 1, pp. 49–58, 1970.

[25] A. Zimmermann and M. Knoke, *TimeNET 4.0: A software tool for the performability evaluation with stochastic and colored Petri nets; user manual.* TU, Professoren der Fak. IV, 2007.

[26] S. Baarir, M. Beccuti, D. Cerotti, M. De Pierro, S. Donatelli, and G. Franceschinis, "The greatspn tool: recent enhancements," *ACM SIGMETRICS Performance Evaluation Review*, vol. 36, no. 4, pp. 4–9, 2009.

[27] P. Bonet, C. M. Lladó, R. Puijaner, and W. J. Knottenbelt, "Pipe v2. 5: A petri net tool for performance modelling," in *Proc. 23rd Latin American Conference on Informatics (CLEI 2007)*, 2007.

[28] M. A. Marsan and G. Chiola, "On petri nets with deterministic and exponentially distributed firing times," in *Advances in Petri Nets 1987*, pp. 132–145, Springer Berlin Heidelberg, 1987.

[29] C. Lindemann and G. S. Shedler, "Numerical analysis of deterministic and stochastic petri nets with concurrent deterministic transitions," *Perform. Eval.*, vol. 27-28, pp. 565–582, Oct. 1996.

[30] C. Lindemann and A. Thümmler, "Transient analysis of deterministic and stochastic petri nets with concurrent deterministic transitions," *Performance Evaluation*, vol. 36, pp. 35–54, 1999.

[31] G. Ciardo, R. German, and C. Lindemann, "A characterization of the stochastic process underlying a stochastic petri net," *Software Engineering, IEEE Transactions on*, vol. 20, no. 7, pp. 506–515, 1994.

[32] S.-S. Tzeng, "Call admission control policies in cellular wireless networks with spectrum renting," *Computer Communications*, vol. 32, no. 18, pp. 1905–1913, 2009.

[33] S.-S. Tzeng and C.-W. Huang, "Threshold based call admission control for qos provisioning in cellular wireless networks with spectrum renting," in *Novel Algorithms and Techniques in Telecommunications and Networking*, pp. 17–22, Springer, 2010.

[34] T. V. Do, N. H. Do, and R. Chakka, "A new queueing model for spectrum renting in Mobile Cellular Networks," *Computer Communications*, vol. 35, pp. 1165–1171, June 2012.