An Application of GSPN for Modeling and Evaluating Local Area Computer Networks

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1. Introduction

Multimedia systems connected by computer networks are widely used in applications such as telecommunications, distance-learning, and video-on-demand (Nerjes et al., 1997;Kornkevn & Lilleberg, 2002;Shahraray et al., 2005). Since multimedia data have real-time properties that must be processed and delivered within given deadlines, the demand on such systems is increasing (Althun et al., 2003;Gibson & David, 2007). In order to maintain the required quality, several systems using QoS techniques have been proposed (Furguson & Huston, 1998;Park, 2006;Villalon et al., 2005). The IEEE802.11e (IEEE Standard, 2003) is one of these techniques. It provides two functions for QoS support: enhanced distributed channel access (EDCA) and hybrid coordination function controlled channel access (HCCA). HCCA uses concentrated control and guarantees the required propagation delay. On the other hand, EDCA uses distributed control, has good scalability, and requires less overhead than HCCA, but cannot guarantee the required propagation delay. In order to assess the dependability of multimedia systems using QoS, such as the IEEE802.11e supporting EDCA, the propagation delay and its standard deviation (jitter) must be quantitatively evaluated (Claypool & Tanner, 1999;Fan et al., 2006;Gibson & David, 2007;Park, 2006).
Several evaluation methods have been proposed, such as queuing networks (Ahmad, et al., 2007;Cheng & Wu, 2005), stochastic process models (German, 2000;Nerjes et al., 1997), and simulation models (Adachi et al., 1998;Bin et al., 2007;Grinnemo & Brunstrom, 2002). However, these methods have several problems. Queuing networks and stochastic process models are analytical models, which do not require a long time for computation. However, it is difficult to model the given systems, since the number of states in a model increases exponentially as the system increases in size, particularly when the systems are large and complex. Though simulation models are used for evaluating systems, they require a long time to obtain statistical data regarding the standard deviation (jitter). This chapter proposes a method for evaluating systems using the Generalized Stochastic Petri Net and the tagged task approach

(Imai et al., 1997;Kumagai et al., 2003). GSPNs are an extension of the Petri Nets that can be easily used to model the timing behavior of systems. The tagged task approach can reduce the number of states in a model by tracing the behavior of a tagged task.
A method for evaluating local area computer network systems, such as the IEEE802.11e WLAN supporting EDCA, based on delay jitter analysis using the Generalized Stochastic Petri Net (GSPN) and the tagged task approach, is fully explained. The system is modeled using GSPN with the tagged task approach, then the state transition diagram of the Markov chain is constructed from the reduced reachability graph of the GSPN model. Processing paths are extracted, and the mean value and variance of the delay time are calculated using the equations derived from the Markov chain. An evaluation example is also given. Section 2 explains system modelling using GSPN, while Section 3 presents the evaluation method that will be used. Section 4 describes the evaluation example, which is a system built using IEEE802.11e WLAN supporting EDCA. Finally, Section 5 summarizes the results of this chapter.

2. Modeling Network Systems Using GSPN

2.1 GSPN

GSPN can be defined as follows (Marson et al., 1995). The set of all natural numbers will be denoted as *N*, while the set of all real numbers will be denoted as *R*.
[Definition1]

$$N_{GSPN} = (P, T, W^-, W^+, W^h, \Lambda, \omega, M_0) \tag{1}$$

$P = \{p_i \mid 1 \le i \le |P| = n\}$; Set of places,

$T = \{t_j \mid 1 \le j \le |T| = m\}$; Set of transitions,

$T = T_I \cup T_T, T_I \cap T_T = \varnothing$; T_I is a set of immediate transitions, T_T is a set of timed transitions,

$W^- : P \times T \to N$; Input connection function,

$W^+ : T \times P \to N$; Output connection function,

$W^h : P \times T \to N$; Inhibitor arcs,

$\Lambda = \{\lambda_i \mid 1 \le i \le |T_T|\}$; Firing rates,

$\omega : T_I \to R$; Weighting function of immediate transitions,

m_0 : Initial marking.

In GSPN, places are represented by circles; timed transitions by boxes; and immediate transitions by thin bars. An inhibitor arc ends in a small circle. A timed transition fires according to the firing rate assigned to the transition when the firing condition is satisfied. Fig.1 shows a typical GSPN for M/M/1/1/3. In the figure, p_1, p_2, p_3, p_4, and p_5 are places; t_1 and t_3 are the timed transitions; t_2 is an immediate transition; and λ_1 and λ_3 are the firing rates for transitions t_1 and t_3.

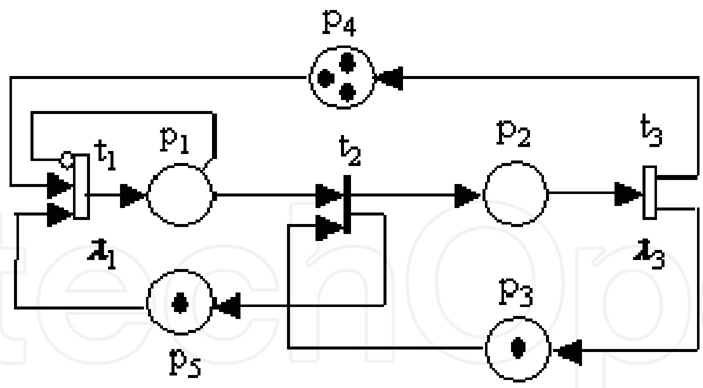


Fig. 1. Sample GSPN

2.2 Reachability Graph and Markov Chain

In the example net, the transition t_1 fires after the time determined by the exponential probability distribution function with parameter λ_1, and the tokens in places p_4 and p_5 move to place p_1. The assignment of tokens to places is called marking. In this example, the marking changes from the initial marking m_0 to the next marking m_1 when t_1 fires, as shown in Fig.2. The change in markings is represented by Equation (2). In Equation (2), $m_0[t_1 > m_1$ indicates that the marking m_0 changes to m_1 after the transition t_1 fires.

$$m_0[t_1 > m_1[t_2 > m_2[t_3 > m_0$$
$$m_0[t_1 > m_1[t_2 > m_2[t_1 > m_3[t_3 > m_0 \quad (2)$$

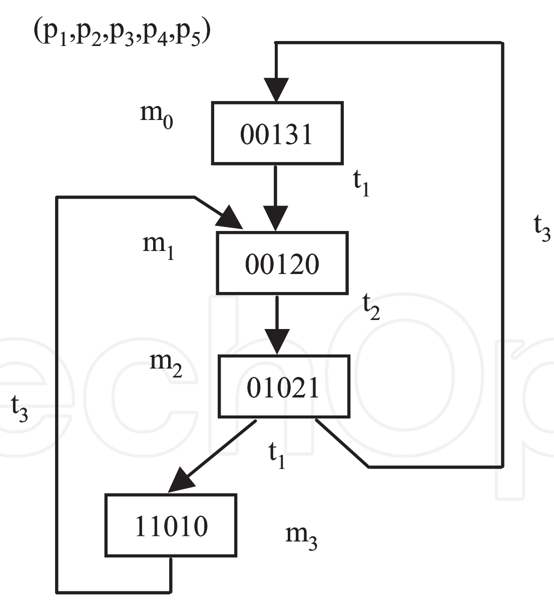


Fig. 2. Reachability graph for the sample GSPN.

The set of markings reached from m_0 is called a reachability set and is defined as follows:
[Definition 2]
The minimum set of markings satisfying the following condition is called the reachability set of the initial marking m_0 and is represented by $RS(m_0)$.

$$
\begin{aligned}
& m_0 \in RS(m_0), \\
& m_1 \in RS(m_0) \wedge \exists t \in T : m_1[t > m_2 \\
& \Rightarrow m_2 \in RS(m_0)
\end{aligned}
\tag{3}
$$
■

The change of markings in a reachability set can be represented by a graph. The graph of all reachable markings from the initial marking is called the reachability graph and is defined as follows.

[Definition 3]

A labeled digraph is called a reachability graph and is represented by $RG(m_0)$ when the set of nodes in the graph is $RS(m_0)$, and the set of edges A in the graph is defined by the following equation:

$$
\begin{aligned}
& A \subseteq RS(m_0) \times RS(m_0) \times T \\
& (m_i, m_j, t) \in A \Rightarrow m_i[t > m_j, m_i, m_j \in RS(m_0)
\end{aligned}
\tag{4}
$$
■

The GSPN has two kinds of markings: tangible and vanishing. Tangible markings allow timed transitions to fire, while vanishing markings allow immediate transitions to fire. Vanishing markings can be reduced by eliminating them from the reachability graph. The reduced reachability graph is equivalent to the state transition diagram of a Markov chain for the GSPN model (Marson et al., 1995) and is shown in Fig.3.

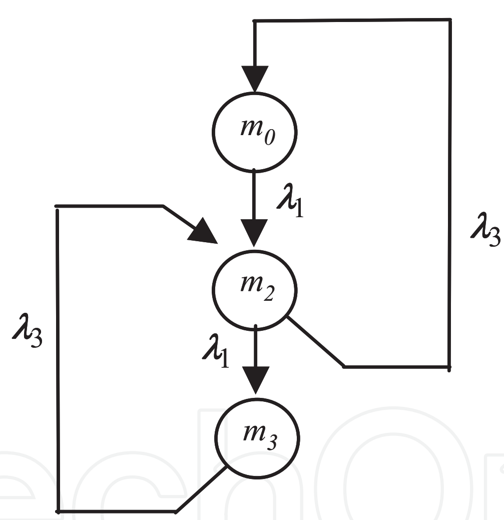


Fig. 3. State diagram of the Markov chain for the sample GSPN.

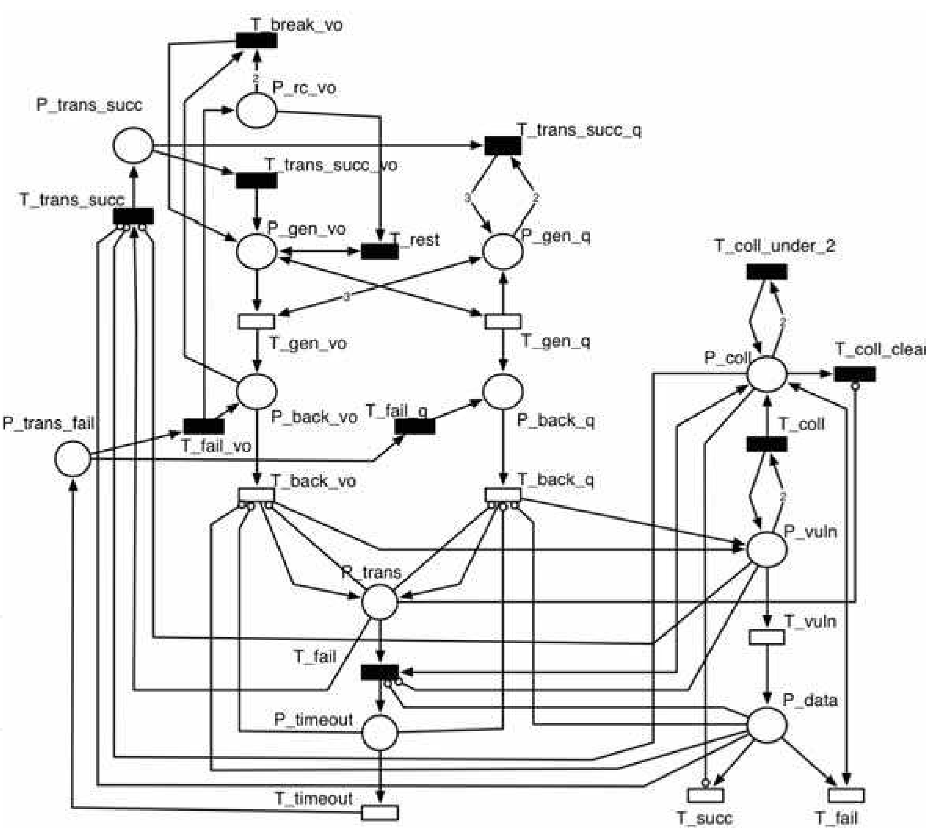
3. System Model

In network systems processing multimedia data with QoS control, tasks are processed according to their priorities for satisfying their QoS requirement. The following system assumptions are useful for analysis.

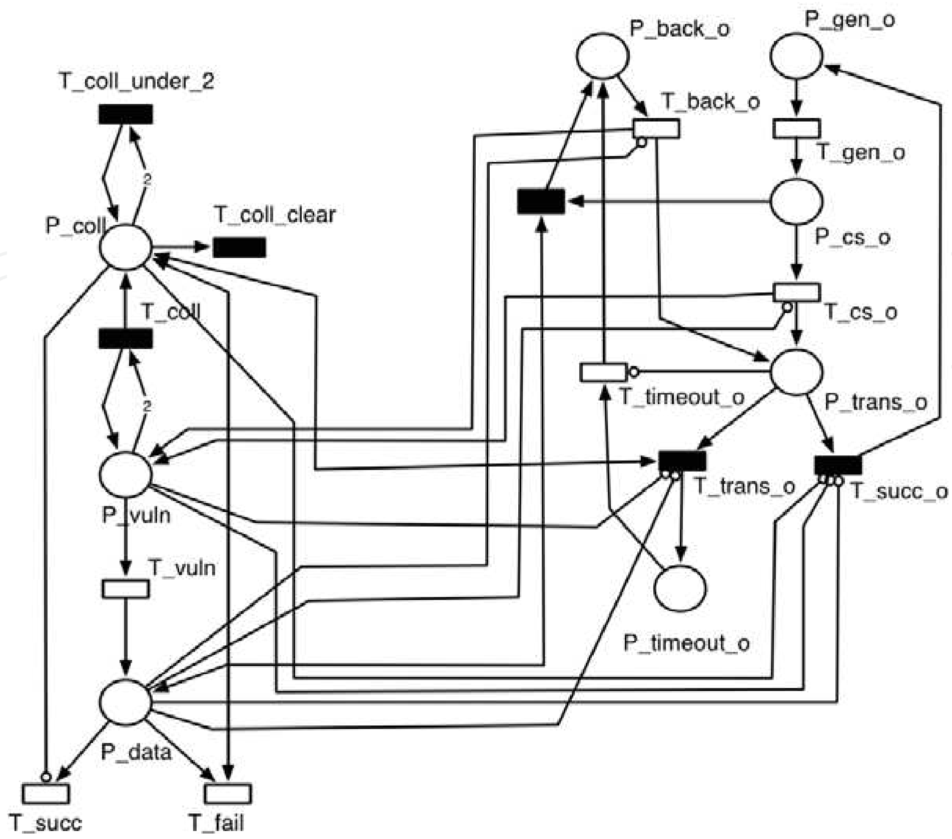
[Assumption1]

Each task has a priority, which determines when it is processed and delivered.

In network systems containing many hosts, tasks occur randomly, and the processing time for tasks may be an arbitrary value. Thus, the following assumptions are made about the tasks:
[Assumption2]
(1) Tasks occur according to a Poisson process.
(2) Task processing time is determined by the exponential probability distribution function.
The IEEE 802.11e WLAN supporting EDCA is used as the example for explaining the system model and the evaluation method. The IEEE 802.11e WLAN supporting EDCA has four access categories (ACs): AC_VO, AC_VI, AC_BE, and AC_BK. The access category AC_VO is the category for voice tasks and has the highest priority. AC_VI is the category for video and has the second-highest priority. AC_BE is the category for best-effort tasks and has the third-highest priority. AC_BK is the category for background tasks and has the lowest priority. The GSPN model for analyzing mean delay and its jitter for the AC_VO task is shown in Fig.4 (Ikeda et al., 2005) (Tsunoyama et al., 2008). The model is constructed based on the tagged task approach in order to decrease the increase in the number of states in the Markov chain.



(a) Target host part.



(b) Nontarget host part.

Fig. 4. GSPN Model of AC_VO in IEEE802.11e WLAN.

In this example, the mean delay and its jitter are analyzed for the AC_VO task generated from a host. In the analysis, the AC_VO task is called the tagged task, and the host is called the target host. Fig.4 (a) shows part of the model and represents the behavior of the tasks from the target host. The right part of the figure represents the interaction between the tasks of the other access categories in the target host and the tasks from the nontarget hosts in the WLAN. Fig.4 (b) also shows part of the model and represents the behavior of tasks from the nontarget hosts in the WLAN.

When an AC_VO task is generated in the target host, the transition *T_gen_vo* fires, and a token moves from *P_gen_vo* to *P_back_vo*. After the back-off time, *T_back_vo* fires and the token moves to *P_trans*. If no task is being sent from the nontarget hosts, the token moves to *P_trans_succ* and also moves back to *P_gen_vo*, since no collision occurs. If another task is being sent from the nontarget hosts, the token moves to *P_timeout* and moves to *P_trans_fail* after the time determined by the firing rate for *T_timeout*. When a task with another access category is generated from the target host, the transition *T_gen_q* fires and a token moves to *P_back_q*. The collision is examined by *T_fail* and *T_timeout,* as with AC_VO.

4. Evaluation Method

4.1 Delivery path and its selection probability

The delay time for task processing can be obtained by accumulating the sojourn time for states in a state sequence from a start state, where the task occurs, to an end state, where the task has been processed and delivered successfully. A reduced reachability graph is equivalent to a state diagram of a Markov chain for task processing. Thus, the delay time can be obtained from the firing rate of transitions in the path corresponding to the state sequence. A path in a reduced reachability graph is defined by the following definition. In the definition, $m_i (a \le i \le b)$ are markings and $t_j (\alpha \le j \le \beta)$ are transitions.

[Definition4]

A sequence of markings and transitions, $m_a [t_a > \dots m_c > t_\beta > m_b]$, starting at marking m_a and ending at marking m_b, for a reduced reachability graph is called a path from m_a to m_b. The number of paths from m_a to m_b is denoted by N_{ab}, while the i^{th} path is denoted by $P_{ab}^{(i)}$ ($1 \le i \le N_{ab}$).

When there are a number of paths from start marking m_a to end marking m_b, task processing is made along one of the paths with the given probability. The probability of a path selected in all paths from m_a to m_b is called the path selection probability and is denoted by $P_r (P_{ab}^{(i)} \mid m_a)$, where $1 \le i \le N_{ab}$.

The probability of transition from marking m_j to next marking m_k is determined by the following equation, where A_j is the set of subscripts of outgoing arcs from the marking m_j (Marson et. al., 1995).

$$\Pr(m_j \to m_k) = \frac{\lambda_j}{\Lambda_j}, \Lambda_j = \sum_{l \in A_j} \lambda_l \tag{4}$$

The path selection probability for path $P_{ab}^{(i)}$ is obtained by the product of the above probabilities for a path and given by the following lemma (Kumagai et al., 2003).

[Lemma1]

$$\Pr(P_{ab}^{(i)} \mid m_a) = \prod_{j=a}^{c} \frac{\lambda_{n_j}}{\Lambda_j} \tag{5}$$

4.2 Sojourn Time for the Path and Delay Jitter

The sojourn time for a path is given by the summation of the sojourn time for all markings in the path. Therefore, the probability density function of the sojourn time for a path can be obtained by the convolution of the probability density function of the sojourn time for every marking in the path. The probability density function of sojourn time, $\tau_{ab}^{(i)}$, for path $P_{ab}^{(i)}$ can be obtained using Equation (5) and Assumption 2. The result is given by the following lemma (Kumagai et al., 2003).

[Lemma2]

$$f_{\tau_{ab}^{(i)}}(t) = -\prod_{j=a}^{b} (-\Lambda_j) \left\{ \sum_{m=a}^{b} \frac{\exp(-\Lambda_m t)}{\prod_{\substack{n=a \\ n \ne m}}^{b} (\Lambda_m - \Lambda_n)} \right\} \tag{6}$$

The mean value E_τ and the variance V_τ of the delay time can be obtained from Equation (6). The following results are presented as a theorem: (Ikeda et al., 2005;Kumagai et al., 2003).
[Theorem1]

$$E_\tau = \sum_{a \in S_{gen}} \Pr(m_a) \sum_{i=1}^{N_{ab}} \left\{ \Pr(P_{ab}^{(i)} \mid m_a) \sum_{j=a}^{b} \left(\frac{1}{\Lambda_j} \prod_{\substack{k=a \\ k \neq j}}^{b} \frac{-\Lambda_k}{\Lambda_j - \Lambda_k} \right) \right\} \tag{7}$$

$$V_\tau = \sum_{a \in S_{gen}} \Pr(m_a) \sum_{i=1}^{N_{ab}} \left[\Pr(P_{ab}^{(i)} \mid m_a) \left\{ \sum_{j=a}^{b} \left(\frac{2}{\Lambda_j^{2}} \prod_{\substack{k=a \\ k \neq j}}^{b} \frac{\Lambda_k}{\Lambda_j - \Lambda_k} \right) - E_\tau^{2} \right\} \right] \tag{8}$$

4.3 Evaluation procedure
Fig.5 shows a flow chart for evaluation. A network is first modeled using GSPN. The GSPN model is then analyzed and a reachability graph is obtained using the Petri Net tool, Time Net (German et al., 1995). The set of start markings is extracted from the reachability graph, and the delivery paths are searched. The delay time and its jitter are calculated for all searched delivery paths.

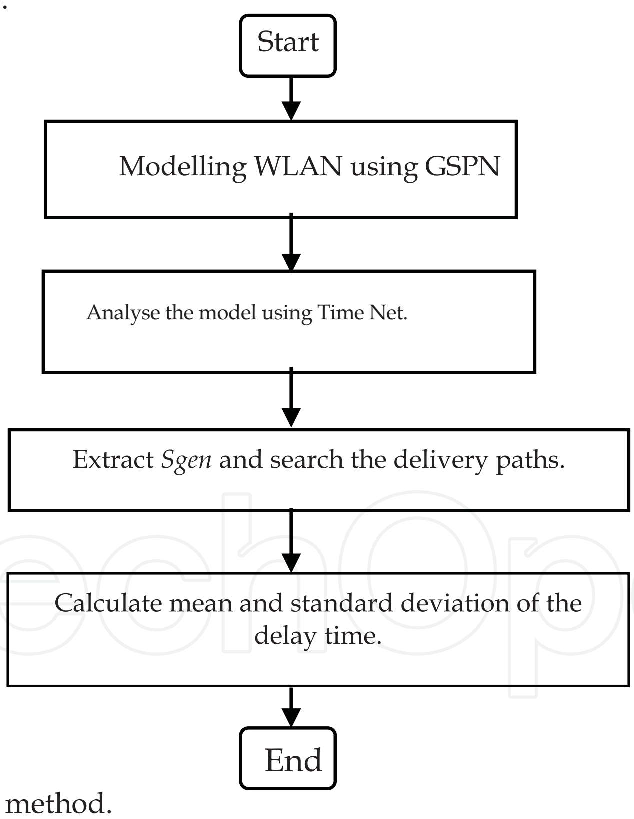


Fig. 5. Flow chart of the method.

5. Example

An example network using IEEE802.11e over the IEEE802.11a consisting of three hosts is evaluated. Table 1 shows the parameters for the simulation.

Access Categories	AIFSN	CW min	CW max	TXOP Limit
AC_BK	7	15	1023	1 frame
AC_BE	3	15	1023	1 frame
AC_VI	2	7	15	3 ms
AC_VO	2	3	7	1.5 ms

Table 1. Parameters for the ACs.

Each AC has four parameters, and ACs are distinguished by assigning different values to the parameters. Table 1 shows the default values for the parameters. A smaller value implies a higher priority. In the example, AC_VO is first analyzed by assigning a tagged task, and then AC_VI is analyzed.

Figs.3 and 4 show the mean delay and jitter for AC_VO and AC_VI, respectively. The figures show that the mean delay for AC_VI increases by about 7.5 [ms] and the jitter for AC_VI increases by about 4.3 [ms] when the virtual load on the network increases from 0.1 to 10.0 . However, when the virtual load increases, the mean delay and jitter for AC_VO decrease by about 1 [ms] less than AC_VI (Ikeda et al., 2005) (Tsunoyama & Imai 2008).

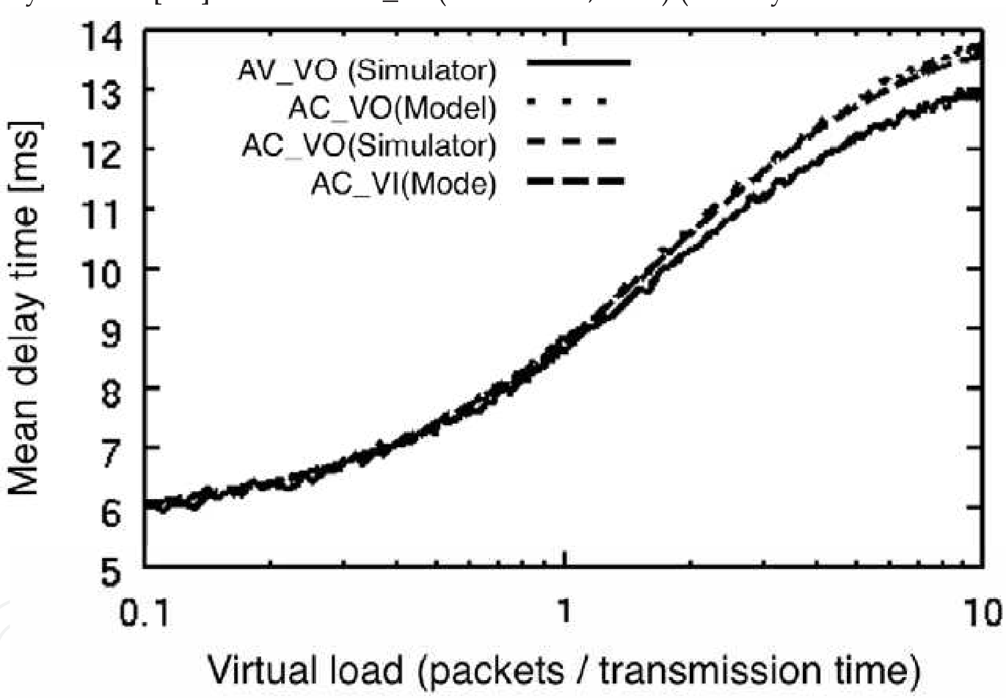


Fig. 6. Mean delay time for AC_VO and AC_VI.

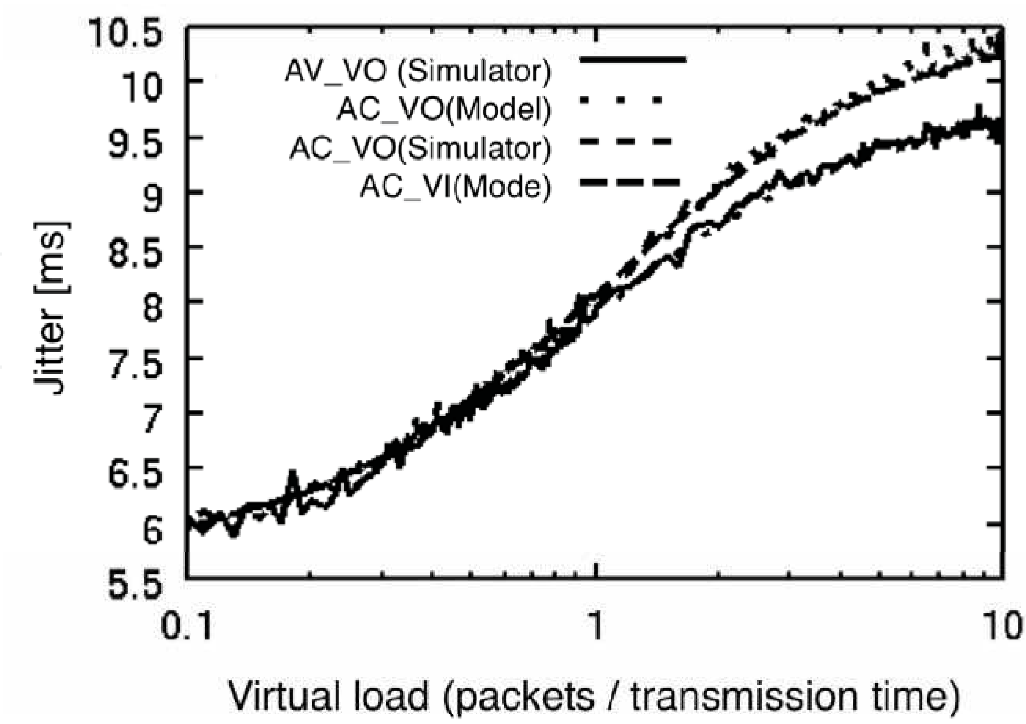


Fig. 7. Jitter for AC_VO and AC_VI.

6. Conclusions

A method for modelling local area computer networks used for processing and delivering multimedia data is proposed. The proposed method can evaluate the mean delay time and its jitter (standard deviation) for systems based on the GSPN model and tagged task approach. The systems can be modeled by the method presented, and both of the values can be evaluated easily using the equations shown in this chapter. An example of modeling and evaluating local area computer networks using IEEE802.11e WLAN supporting EDCA was shown. From the results, it can be concluded that the system can be modeled easily. The mean delay and jitter for AC_VO obtained using the proposed method agrees well with the values obtained using simulations. However, when the virtual load of the network exceeds one, the value of the jitter for AC_VI differs slightly from that by simulation.
Future efforts will improve the model to reduce the observed difference and to compose a compact model to reduce the number of states in the Markov chain for the network.

7. Acknowledgements

The authors would like to thank Messrs. Kumagai, Ikeda, and Maruyama for their helpful discussions and comments. The authors would also like to thank Professor Ishii and Professor Makino for their helpful comments.

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Petri Nets Applications
Edited by Pawel Pawlewski

ISBN 978-953-307-047-6
Hard cover, 752 pages
Publisher InTech
Published online 01, February, 2010
Published in print edition February, 2010

Petri Nets are graphical and mathematical tool used in many different science domains. Their characteristic features are the intuitive graphical modeling language and advanced formal analysis method. The concurrence of performed actions is the natural phenomenon due to which Petri Nets are perceived as mathematical tool for modeling concurrent systems. The nets whose model was extended with the time model can be applied in modeling real-time systems. Petri Nets were introduced in the doctoral dissertation by K.A. Petri, titled "„Kommunikation mit Automaten" and published in 1962 by University of Bonn. During more than 40 years of development of this theory, many different classes were formed and the scope of applications was extended. Depending on particular needs, the net definition was changed and adjusted to the considered problem. The unusual "flexibility" of this theory makes it possible to introduce all these modifications. Owing to varied currently known net classes, it is relatively easy to find a proper class for the specific application. The present monograph shows the whole spectrum of Petri Nets applications, from classic applications (to which the theory is specially dedicated) like computer science and control systems, through fault diagnosis, manufacturing, power systems, traffic systems, transport and down to Web applications. At the same time, the publication describes the diversity of investigations performed with use of Petri Nets in science centers all over the world.

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