A Time-Constrained Information Processing Model in Ubiquitous Environments

Sun Hur, Hyun Lee, Dongmin Shin, and Wonsuk Lee

As pervasive computing is widely adopted and reliable networks are becoming more easily accessible, there is a rapidly growing need to develop a mechanism to analyze and evaluate the performance of ubiquitous environments. This paper presents an information processing model which characterizes a ubiquitous environment where a variety of pieces of information need to be exchanged among devices within a system. The proposed model not only provides analytical tools to evaluate the performance of devices, but also makes it possible to identify key factors in designing a ubiquitous environment. For illustrative purposes, a test bed is constructed and the performance of the system is assessed based on the proposed model.

Keywords: Analytical tool, performance measurement, information processing model, ubiquitous environment.

I. Introduction

For the management of a complex system, it is necessary to identify the crucial factors and characterize their features in relation to the system behavior. A complex system is characterized in part by uncertain dynamic behavior, as well as heterogeneous and temporal aspects.

Recently, ubiquitous environments have rapidly evolved as smart devices, fast and reliable networks, and high-performance computing technologies have become available. Devices such as electrical appliances, cellular phones, and personal digital assistants (PDAs) have enabled users to have access to desired information any time, anywhere. Moreover, Web services, which are widely gaining popularity, enable effective information sharing on the Web, through which a variety of devices can be connected.

A ubiquitous environment can be described as a system which provides services by associating, correlating, and combining information collected from multiple sources. Specifically, it means an environment in which a variety of interconnected devices cooperate to provide appropriate services (or take actions) based on information about states of the system. Changes of states can be described with information packets which are exchanged between devices involved in the system.

To provide appropriate services based on a large volume of different types of information in a ubiquitous environment, information exchange and sharing among heterogeneous entities needs to be managed in an efficient and effective manner. Furthermore, as computer technologies advance, information fusion is considered a vital aspect in information systems.

In designing a ubiquitous environment where a variety of

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devices are involved, it is important to model and analyze the communication behavior of those devices so that appropriate information can be delivered and processed for high-quality services. In particular, modern information systems are characterized by composite services consisting of multiple subcomponents, each of which delivers diverse information.

In particular, a ubiquitous environment needs to be designed in such a way that each device is coordinated to meet temporal requirements, such as any condition on the timing of events, including starting the event, terminating the event, checking the time delay in a service, and time synchronization. Therefore, in a real system, time is an important issue for performance analysis of the systems and real-time ubiquitous systems that have constraints on the exact timing of the service invocation.

Motivated by this, we present an analytical model based on the queueing theory to evaluate the performance of information systems associated with the implementation of a real-time ubiquitous environment. The model presented in this paper can be used to identify the key factors and specify operation strategies for a ubiquitous system.

The remainder of this paper is organized as follows. Section II discusses the background of this work by presenting the motivation of this research as well as related work. In section III, an information processing model is presented and its implications for an effective real-time ubiquitous environment are discussed. Illustrative examples and an application test bed based on the proposed model are provided in sections IV and V, respectively. Section VI summarizes the paper and suggests future research directions.

II. Research Background

In a ubiquitous environment, users can avail of services which provide information over the Internet by means of various communication devices anytime anywhere. Moreover, each service needs to provide personalized information which is mostly collected from multiple devices. In this process, the temporal aspect should be taken into account for effective operations of the system because the majority of information can become obsolete at some point after it is gathered. This is particularly critical in a dynamically changing environment.

Services in a ubiquitous environment can be considered mechanisms which interpret, process, and produce information. Information can be considered as an object which is engineered and manufactured in a somewhat similar way to that in which other products are produced, although there are several differences between physical products and information objects.

Sun and Yen [1] consider information as an entity which is delivered in response to demands, and they propose an information supply chain framework for information sharing. They study states of information by making an analogy to states of matter. Data, knowledge, and models are compared to gases, liquids, and solids, respectively, and these analogies are used to characterize states of information [2].

A significant amount of research has been conducted in the area of information systems for a ubiquitous environment. How to combine a variety of information gathered from different sources is presented in [3], [4]. The authors review and compare several information combination operators to process multiple data. To evaluate information systems, several approaches have been taken, which include fuzzy theories and Bayesian networks [5], [6]. Specifying service requirements has been considered a critical step in developing and implementing information combination systems, and much research has been conducted in the software requirements area [7]-[9]. Most of the research, however, focuses on what the system should do rather than how the requirements should be implemented.

Despite the amount of research that has been undertaken to specify the state and behavior of information, an analytical approach to analyze and evaluate information objects is still desirable. Moreover, the temporal issue associated with information processing that involves multiple sources has not received much attention. Since information processing plays an important role in a ubiquitous environment, its behavior and its impact on the performance of systems must be identified and clearly analyzed.

III. Time Constrained Information Processing

1. The Model

In this section, we describe an information processing system which is composed of one or more objects incorporating multiple pieces of information, called information packets, under time constraints. Figure 1 depicts a typical information processing device, such as a PDA, in the system.

A device in the system collects randomly generated information packets from other entities and/or outside of the system. We use the term “packets” in the sense that these may not be meaningful by themselves to the devices until they are interpreted or processed. When the accumulated information packets satisfy a predefined condition within a device, the device can process them to provide a service. More specifically, when the number of information packets received by the device exceeds a threshold, the device interprets these packets together to make a meaningful information object. A meaningful information object refers to a part of a protocol which can trigger a service in accordance with predefined operational rules of the device.

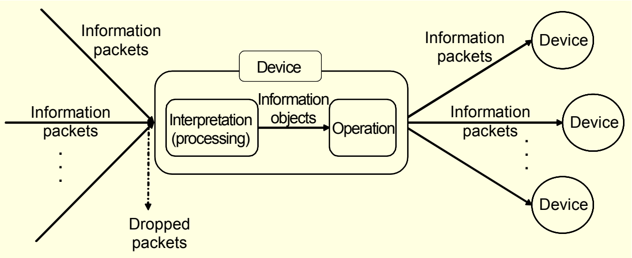

Fig. 1. Information processing device.

The information packets which arrive at the device, however, may become obsolete as time elapses and should be removed before being processed after a certain amount of time. For example, previous weather information can be of no use if new weather forecasting information arrives.

There may be several different types of information packets with their own thresholds, each of which forms a corresponding type of information object. The formed information object then triggers the device to perform an operation and the device sends new information packets to other devices in the system. We call the overall time from the moment the first information packet arrives at the device until it completes the operation the device's response time. The response time should be within a predetermined time to be meaningful to the subsequent devices in the system, that is, the device has a time constraint.

The following assumptions are made to model the information processing procedure described above.

- The arrival stream of information packets to a device is a Poisson process. Information packets waiting at the device to be processed (or interpreted) may be obsolete and removed from the device, which also occurs according to a Poisson process.
- The device's processing time is exponentially distributed, but the operating time is constant κ.[1]
- The number of devices in the system is large enough; therefore, there is no chance of running out of information packets.

2. Average Time to Process One Type of Information

First, we consider that there is only one type of information packet. The device begins its information packet processing when there are n packets accumulated. The packet arrival rate is λ, and the packet removal rate is α. In particular, priority mechanisms should include the concept of quality or importance of the information packets, such as completeness, integrity, reliability, timeliness, and so forth. In general, it is not always possible to determine the priority (or importance) of an arriving packet until it has been processed. Therefore, we assume the device deals with all packets with equal priority. Instead, timliness is addressed by introducing the packet removal rates. Figure 2 illustrates a typical change in the number of information packets in a device.

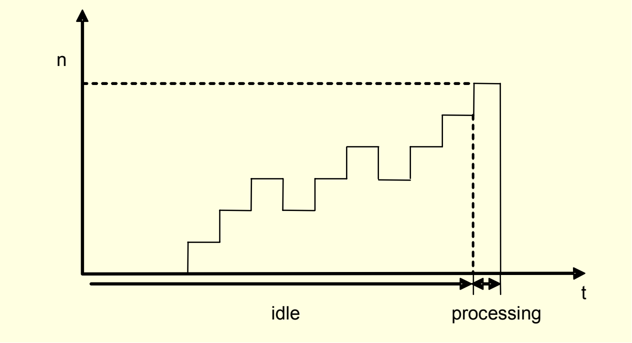

Fig. 2. Typical change of the number of packets.

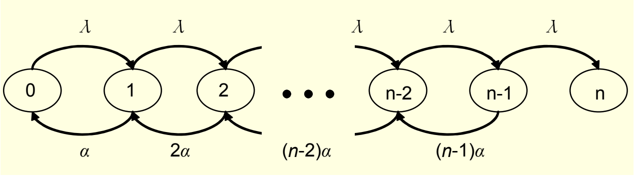

Fig. 3. Transition rates diagram of $\{N(t), t \geq 0\}$.

In reality, the system parameters should be determined on the basis of the effects of interaction among the system entities. For example, under the wireless environment, the entities' mobility and the limited range of communication do affect the dynamic status of the system, which could be captured through the input parameters. For example, the increasing mobility of each entity makes the information packet arrival rate λ higher as well as the removal rate α.

Let $\{N(t), t \geq 0\}$ be a random process with state space $E=\{0, 1, 2, \cdots, n-1, n\}$, where $N(t)$ is the number of packets at time t, and the process is absorbed by state n. It is assumed that $\alpha < \lambda$. Figure 3 depicts the transition rates diagram of this process.

Let T_k denote the time it takes for the process to be absorbed by state n, starting from state k ($k=0,1,2,\cdots, n-1$). It is the time until the number of information packets reaches threshold n, given that there are currently k packets. Then $E(T_0)$ is the expected time for the device to begin its processing for the first time or after completing an operation. We recursively compute $E(T_k)$, starting with $k=0$. Since the process can move from 0 to state 1 by the arrival of a packet in an exponentially distributed time whose average is $1/\lambda$, we have

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[1] This assumption corresponds to the performance of devices. Information processing is closely related with the computation of a device whereas the operation depends on the communication.

$$E(T_0) = E(T_1) + \frac{1}{\lambda}. \tag{1}$$

For $k=1, 2,\cdots, n-1$, we determine whether the first transition takes the process into $k-1$ or $k+1$. Since the first transition is either from arrival or removal of a packet with probabilities $\lambda/(\lambda+k\alpha)$ and $k\alpha/(\lambda+k\alpha)$, respectively, and the transition time is exponential with rate $\lambda+k\alpha$, we see that

$$\begin{aligned} E(T_k) &= \frac{k\alpha}{\lambda+k\alpha}\left(\frac{1}{\lambda+k\alpha} + E(T_{k-1})\right) \\ &\quad + \frac{\lambda}{\lambda+k\alpha}\left(\frac{1}{\lambda+k\alpha} + E(T_{k+1})\right), \quad k = 1,2,\cdots,n-1. \end{aligned} \tag{2}$$

Note that $E(T_n) = 0$.

Rearranging (1) and (2) yields

$$\begin{aligned} E(T_0) - E(T_1) &= \frac{1}{\lambda}, \\ E(T_1) - E(T_2) &= \frac{\alpha}{\lambda}[E(T_0) - E(T_1)] + \frac{1}{\lambda} = \frac{\alpha}{\lambda}\left(\frac{1}{\lambda}\right) + \frac{1}{\lambda}, \\ &\vdots \\ E(T_{n-2}) - E(T_{n-1}) &= (n-2)\frac{\alpha}{\lambda}\left[E(T_{n-3}) - E(T_{n-2})\right] + \frac{1}{\lambda}, \\ E(T_{n-1}) &= \frac{(n-1)\alpha}{\lambda}\left[E(T_{n-2}) - E(T_{n-1})\right] + \frac{1}{\lambda} \\ &= \frac{(n-1)\alpha}{\lambda}\left(\cdots\left(\frac{2\alpha}{\lambda}\left(\frac{\alpha}{\lambda}\left(\frac{1}{\lambda}\right) + \frac{1}{\lambda}\right) + \frac{1}{\lambda}\right)\cdots\right) + \frac{1}{\lambda}. \end{aligned} \tag{3}$$

By summing both terms of (3), we finally obtain

$$E(T_0) = \frac{1}{\lambda}\left[\sum_{j=1}^{n-1}\prod_{k=1}^{j}\frac{k\alpha}{\lambda} + \sum_{i=2}^{n-1}\sum_{j=i}^{n-1}\prod_{k=i}^{j}\frac{k\alpha}{\lambda} + n\right], \tag{4}$$

$$E(T_k) = \frac{1}{\lambda}\left[\sum_{j=k}^{n-1}\prod_{l=1}^{j}\frac{l\alpha}{\lambda} + \sum_{i=2}^{n-1}\sum_{j=k}^{n-1}\prod_{l=i}^{j}\frac{l\alpha}{\lambda} + (n-k)\right], \quad 1 \le k \le n-1. \tag{5}$$

Now, $E(T_0) + 1/\mu + \kappa$ is the total expected response time of the device with one type of information packet, where $1/\mu$ is the expected processing time, and κ is the device's operation time.

3. Average Time to Processing Multiple Types of Information

It is not unusual in ubiquitous environments for multiple types of information packets from different sources to be delivered to a device. With each type of information packet, the device should perform different types of processing to yield different kinds of information objects. After all data packets are processed to become information objects, the device can perform the operation to yield new information packets, which are transmitted to other downstream devices. This is a chain of services provided in a ubiquitous environment.

In this section, we extend the average response time of the information processing presented in the previous section to the case where there is more than one type of information packet. The device processes those information packets sequentially in the order in which their thresholds are reached. We focus first on the case in which there are two types of packets, with which the device performs two types of processing and produces two information objects. Then we extend our focus to the cases in which there are $m(m \ge 3)$ types.

The thresholds of each type of packet are denoted by n_1 and n_2, respectively. The arrival rates and the drop rates of each type are λ_i and $\alpha_i (i = 1, 2)$, respectively. Define $T^{(1)}$ as the time until the device begins processing the information packets which meet the threshold first. Additionally, $T^{(2)}$ is the time from the moment the device finishes processing the first type of packet to the point at which it begins the second processing. The device's total expected response time is

$$E(T) = E(T^{(1)}) + 1/\mu_1 + E(T^{(2)}) + 1/\mu_2 + \kappa, \tag{6}$$

where $1/\mu_1$ and $1/\mu_2$ are the expected information processing times of each type.

It can be easily seen that $E(T^{(1)})=E(T_0)$, where $E(T_0)$ is as given in (4) with $n=n_1$, $\lambda=\lambda_1$, and $\alpha=\alpha_1$. As for $E(T^{(2)})$; however, it depends on K, the number of information packets of the second type accumulated in the device at the time the first processing is completed. For example, Figs. 4 to 6 show the cases $K=n_2$, $K=0$, and $1 \le K \le n_2 - 1$, respectively. Therefore, it is necessary to obtain the probability distribution of K to calculate $E(T^{(2)})$.

For this purpose, we introduce another random process, $\{M(t), t \ge 0\}$, with state space $E = \{0,1,2,\cdots,n-1,n\}$, where $M(t)$ is the number of information packets at time t, where the process enters back to state 0 in exponential time with rate μ,

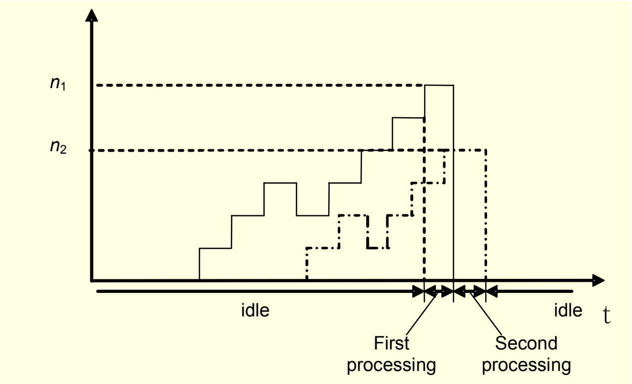

Fig. 4. Case $K = n_2$.

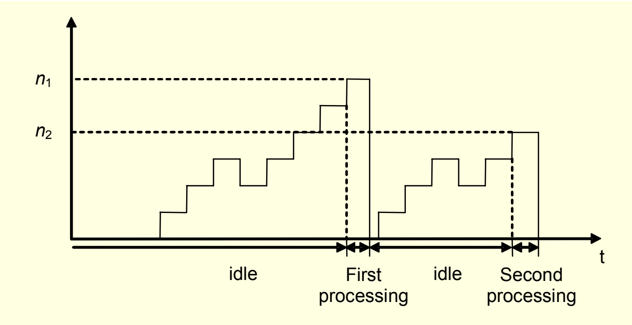

Fig. 5. Case $K = 0$.

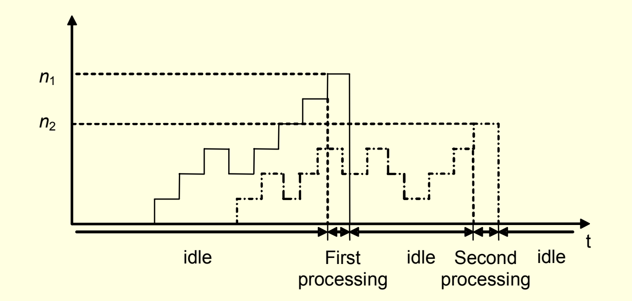

Fig. 6. Case $1 \le K \le n_2-1$.

whose state transition rate diagram is given in Fig. 7. Notice that this process is different from $\{N(t), t \ge 0\}$, introduced in the previous section, in that it does not have an absorbing state.

Define $P_k \equiv \Pr(K = k) = \lim_{t\to\infty} \Pr(M(t) = k)$ as the steady-state probabilities of this process for $k = 0,1,\cdots,n$. Then we have

$$\begin{aligned} \mu P_n &= \lambda P_{n-1}, \\ (\lambda + (n-1)\alpha)P_{n-1} &= \lambda P_{n-2}, \\ &\vdots \\ (\lambda+\alpha)P_1 &= \lambda P_0 + 2\alpha P_2, \\ \lambda P_0 &= \alpha P_1 + \mu P_n. \end{aligned} \tag{7}$$

Using (7) and the boundary condition $\sum_{i=0}^{n} P_i = 1$, we have

$$\begin{aligned} P_k &= \frac{\mu}{\lambda}\left[\sum_{l=0}^{n-2}\left[\frac{\mu}{\lambda}\sum_{i=l+1}^{n-1}\prod_{j=l+1}^{i}\frac{j\alpha}{\lambda}\right]+\frac{\mu}{\lambda}(n-1)+1\right]^{-1} \\ &\quad \times\left[1+\sum_{i=k+1}^{n-1}\prod_{j=k+1}^{i}\frac{j\alpha}{\lambda}\right], 0 \le k \le n-2, \\ P_{n-1} &= \frac{\mu}{\lambda}\left[\sum_{l=0}^{n-2}\left[\frac{\mu}{\lambda}\sum_{i=l+1}^{n-1}\prod_{j=l+1}^{i}\frac{j\alpha}{\lambda}\right]+\frac{\mu}{\lambda}(n-1)+1\right]^{-1}. \end{aligned} \tag{8}$$

By means of the equations above, we finally obtain

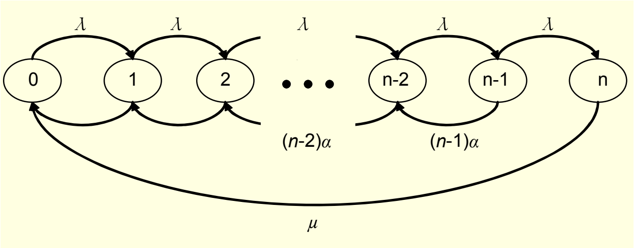

Fig. 7. Transition rates diagram of $\{M(t), t \ge 0\}$.

$$E(T^{(2)}) = \sum_{k=0}^{n} E(T_k^{(2)})P_k^{(2)}, \tag{9}$$

where $E(T_k^{(2)})$ is given by (5) with $n=n_2$, $\lambda=\lambda_2$, and $\alpha=\alpha_2$. $P_k^{(2)}$ is obtained from (8) with $n=n_2$, $\lambda=\lambda_2$, $\alpha=\alpha_2$ and, $\mu=\mu_2$.

Now we extend the above result to the general case in which there are $m(m \ge 3)$ types of information packets to be processed by the device. We define $T^{(i)}(i = 2,3,\cdots,m)$ as the time from the moment that the device completes the $(i-1)$th processing until it begins the i-th processing. Denoting the arrival rates, drop rates, processing rates, and thresholds of type i by λ_i, α_i, μ_i, and n_i, we have

$$E(T^{(i)}) = \sum_{k=0}^{n_i} E(T_k^{(i)})P_k^{(i)}, \tag{10}$$

where $E(T_k^{(i)})$ is given by (5) with $n=n_i$, $\lambda=\lambda_i$, and $\alpha=\alpha_i$, and $P_k^{(i)}$ is obtained from (8) with $n=n_i$, $\lambda=\lambda_i$, $\alpha=\alpha_i$, and $\mu=\mu_i$.

Now, the device's overall expected response time is given by

$$E(T) = \sum_{i=1}^{m}\left[E(T^{(i)}) + \frac{1}{\mu_i}\right] + \kappa. \tag{11}$$

IV. Numerical Examples

We provide numerical examples in this section which illustrate the computation based on the model presented in the previous sections. We identify the key factors among the various parameters which have a significant impact on the information system performance. This can be used to specify operation strategies for a ubiquitous environment.

Suppose there are three types of packets which arrive at the device, and we calculate the total expected time until the device finishes processing all three types under various values of arrival rate (λ) and drop rate (α). The device's operation time, κ, is fixed at 3. For simplicity, we assume $\lambda_1 = \lambda_2 = \lambda_3 \equiv \lambda$ and $\alpha_1 = \alpha_2 = \alpha_3 \equiv \alpha$.

Numerical data of each parameter is given in Table 1.

Data set (i) is used to observe the effect of various values of λ and α on the response time, while data set (ii) is used to assess

Table 1. Data for numerical examples.

Data set	n_i	$1/\mu_i$	λ	α
(i)	(5, 10, 15)	(1/2, 1/4, 1/5)	10 to 50	1 to 5
(ii)	(5, 10, 15)	(1/4, 1/8, 1/10)	10 to 50	1 to 5
(iii)	(1, 3, 5) to (11, 13, 15)	(1/2, 1/4, 1/5)	30	3

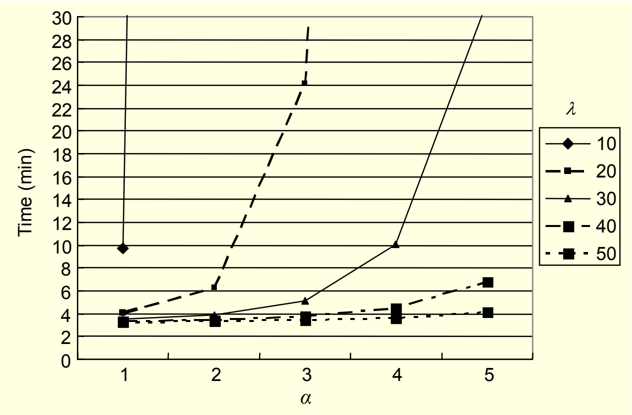

Fig. 8. Case of data set (i).

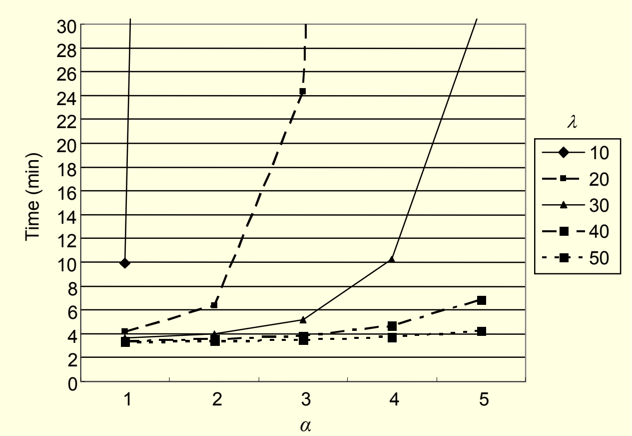

Fig. 9. Case of data set (ii).

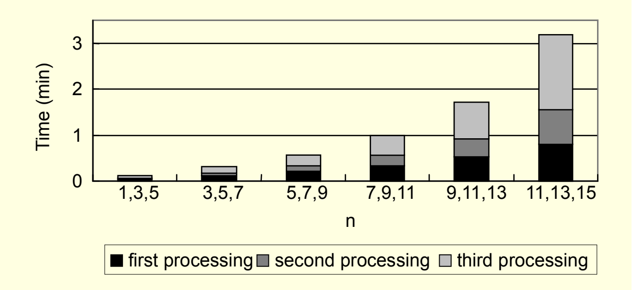

Fig. 10. Case of data set (iii).

the effect of information processing time by comparing the response times with the case of data set (i). Data set (iii) is used to identify the effects of thresholds. The response times computed by (10) for each data set are shown in Figs. 8, 9, and 10, respectively.

Figure 8 shows that changes in λ and α drastically impact the response time. We see, however, almost no significant difference between Figs. 8 and 9, which implies that the information processing time ($1/\mu_i$) is not an important factor in the total response time.

In addition to changes of λ and α, from Fig. 10, it can be observed that the threshold is another key factor which greatly affects the response time. We can interpret the threshold as a measure of the quality of information since, if the device gathers more information with higher thresholds, it can evidently improve the quality of information objects. However, as the thresholds become higher, the response time increases drastically as seen in Fig. 10. Therefore, there is a trade-off between the quality of information and the response time, and a proper threshold level needs to be determined.

V. Application to a Traffic Information System

In this section, we apply the analytical model developed in this paper to demonstrate its applicability. We especially focus on a traffic control information system consisting of numerous devices (traffic lights, patrol cars, road sensors, passenger cars, trucks, driver's PDA, traffic control stations, and so on) and information packets concerning various conditions and events, such as highway congestion, accidents, weather, car speed, road construction, and so on). A traffic control station covering an area with a radius of approximately 3 to 5 km gathers the information packets from various devices. The collected information packets are processed by the station and the newly formed traffic information is transmitted to users, such as traffic lights, patrol cars, and navigation systems in vehicles.

Specifically, there are n_1 patrol cars in the region which send information packets regarding conditions and events, including traffic accidents, road construction, and temporary congestion. We denote the set of information packets which the patrol cars send to the traffic control station as $P=(I_1^P, I_2^P, \cdots, I_{n_1}^P)$, where I_i^P is the information packet from the patrol car $i (i=1,2,\cdots,n_1)$. In addition, the road sensors within the area send information packets $R=(I_1^R, I_2^R, \cdots, I_{n_2}^R)$, where $I_i^R (i=1,2,\cdots,n_2)$ is the information packet from the road sensor *i*. The traffic control station may also gather information from the vehicles directly, such as speed, vehicle type, and destination. The set of information packets from the vehicles is denoted as $V=(I_1^V, I_2^V, \cdots, I_{n_3}^V)$, where $I_i^V = (i=1,2,\cdots,n_3)$ is the information packet from vehicle *i*. The traffic control station collects n_1, n_2, and n_3 information packets from

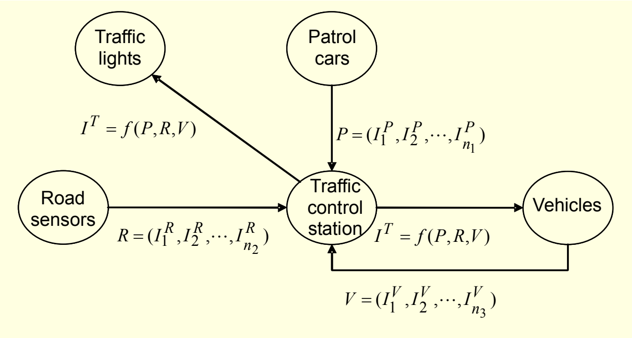

Fig. 11. Traffic information system.

patrol cars, road sensors, and vehicles, respectively. It interprets (or processes) those packets, and produces a new traffic information packet $I^T = f(P, R, V)$, where mapping f is a proper operation to build information packets from total $n_1+n_2+n_3$ packets. Since the traffic condition at a specific location frequently changes in a dynamic and unexpected way, it is important for the station to provide effective services by delivering updated information to each device in the system. Therefore, the information packet I^T should be made up and transmitted by the station within time τ. The traffic information system presented above is depicted in Fig. 11.

For this system, the patrol cars, road sensors, and vehicles send their information packets as Poisson processes with common rate $\lambda_1 = \lambda_2 = \lambda_3 = 9$ or 13 per minute, but some packets turn out to be obsolete or irrelevant and are therefore removed according to a Poisson process at a rate of $\alpha_1 = \alpha_2 = \alpha_3 = 1$ per minute. The traffic control station processes the packet sets P (from the patrol cars), R (from the road sensors), and V (from the vehicles) in exponentially distributed times with means of $1/\mu_1=1/5$, $1/\mu_2=1/10$, and $1/\mu_3=1/15$ (in minutes), respectively. The station's operation time is $\kappa = 0.10$ minutes, and it should complete its response within $\tau=5$ minutes, This enables an arbitrary driver to receive updated traffic information every 5 minutes, and if his or her vehicle's speed is approximately 40 km/h, a maximum of three updates is possible within the area (with the assumption that the vehicle proceeds in one direction).

We calculate the total expected response time of the traffic control station when the numbers of patrol cars, road sensors, and vehicles to collect the packets can be $(n_1, n_2, n_3) = (7, 9, 11)$, (9, 11, 13), or (11, 13, 15). Table 2 summarizes the total expected response time of the traffic control station for each case.

From Table 2, it can be concluded that when $\lambda=9$, only the option $(n_1, n_2, n_3) = (7, 9, 11)$ meets the time constraint of $\tau=5$ minutes. This means the station should utilize fewer information packets in order to produce timely information, but this inevitably degrades the quality of information. When $\lambda=13$ (or higher), however, all three cases meet the time constraint and the traffic control station can provide the devices in the system with traffic information of higher quality.

Table 2. Response times of traffic station.

(n_1, n_2, n_3)	Response time (min)	
	$\lambda = 9, \alpha = 1$	$\lambda = 13, \alpha = 1$
(7, 9, 11)	4.73	2.46
(9, 11, 13)	8.16	3.43
(11, 13, 15)	16.08	4.91

VI. Conclusion

Smart devices, reliable and fast networks, and computer technologies are contributing considerably to the development of ubiquitous environments. While technological advances play an important role in the emerging ubiquitous environment, it is desirable to be able to analyze and assess the performance of the whole system to design an efficient and effective system. The key factors which determine the quality of services provided to users also need to be clearly identified.

The fact that the operations of a device are mostly triggered by those of other devices imposes a need for a methodology which enables the analysis of system performance which considers interconnectivity between devices. Operations of devices can be described as events which are driven by multiple pieces of information received from a variety of sources. Furthermore, information can sometimes become obsolete at a certain point of time due to the dynamically changing environment.

This paper presented an analytical model which enables the evaluation of the performance of a ubiquitous environment where multiple devices are interconnected by exchanging pieces of information to provide services by delivering meaningful information. Based on the model proposed in this paper, the key factors that influence the response times and the quality of service can be identified and their impact investigated.

The model has been developed in a way that generic behavior of multiple devices based on gathered information can be described by means of queueing theory. In particular, the temporal issue which is critical in a dynamically changing environment has been considered. As an illustrative example, a traffic control system was considered, and the performance of the control station was assessed. Based on the proposed model, the number of information packets to compose a service was identified as the most critical factor influencing response time.

This implies that more effort needs to be put into the quality of services and the architecture of systems needs rather than improvement of the computational performance of individual devices.

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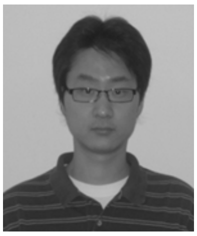

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