Reliability Analysis for Various Communication Schemes in Wireless CORBA

Xinyu Chen and Michael R. Lyu, *Fellow, IEEE*

***Abstract*—For the purpose of designing more reliable networks, we extend the traditional reliability analysis from wired networks to wireless networks with imperfect components. Wireless network systems, such as wireless CORBA, inherit the unique handoff characteristic which leads to different communication structures with various components & links. Therefore, the traditional definition of two-terminal reliability is not applicable anymore. We propose a new term, end-to-end expected instantaneous reliability, to integrate those different communication structures into one metric, which includes not only failure parameters but also service parameters. Nevertheless, it is still a monotonously decreasing function of time.**

The end-to-end expected instantaneous reliability, and its corresponding MTTF, are evaluated quantitatively in different wireless communication schemes. To observe the gain in overall reliability improvement, the reliability importance of imperfect components are also evaluated. The results show that the failure parameters of different components take different effects on MTTF & reliability importance. With different expected working time of a system, the focus of reliability improvement should change from one component to another in order to receive the highest reliability gain. Furthermore, the number of engaged components during a communication state is more critical than the number of system states.

For simplicity, we assume that the wired & wireless communication links are perfect, and omit them in the reliability analysis. If these two are engaged into the proposed end-to-end expected instantaneous reliability, it can give a more detailed & complete reliability assessment of a wireless network system. Our quantitative measurements are conducted as an example with the assumption that the failure & service rate are constant; however, in practice, failure & service processes may follow other distributions. After all, our investigation provides an initial yet overall approach to measure the reliability of wireless networks. Although our analysis is conducted on wireless CORBA platforms, it is easily extensible to generic wireless network systems.

***Index Terms*—End-to-end expected instantaneous reliability, handoff, reliability importance, wireless CORBA.**

ACRONYMS[1]

AB	Access Bridge
CORBA	Common Object Request Broker Architecture
EIR	Expected Instantaneous Reliability
GIOP	General Inter-ORB Protocol
HLA	Home Location Agent
IIOP	Internet Inter-ORB Protocol
IOR	Interoperable Object Reference
MH	Mobile Host
MIOR	Mobile IOR
MSS	Mobile Support Station
MTTF	Mean Time To Failure
OMG	Object Management Group
ORB	Object Request Broker
RI	Reliability Importance
SH	Static Host
r.v.	random variable

NOTATION

$\alpha, \beta, \gamma, \delta$	failure rate
η	handoff completion rate
ν	location-forwarding rate
ρ	handoff rate
$n_c(s)$	number of component c engaged in state s, $c \in \{mh, ab, sh, hla\}$
$n(s)$	number of components engaged in state s
n_c	number of component c, $c \in \{mh, sh\}$
$ER_s(t)$	end-to-end EIR for scheme s, $s \in \{ss, ms, sm, mm\}$
$I_{R_i}(t)$	RI of component i, $i \in \{mh, ab, sh, hla\}$
$\pi_s(t)$	$\Pr\{\text{state } s\}$, $s \in \{a, b, \ldots, r\}$
$R_s(t)$	reliability of state or component s, $s \in \{a, b, \ldots, r, mh, ab, sh, hla\}$

I. INTRODUCTION

NETWORK-RELIABILITY analysis has long been an important area of research for wired networks [1]–[5] but not for wireless networks. As mobile technology matures, however, wireless networks [6] are employed in more applications, and provide mobile users ubiquitous & continuous access to computing resources. Wireless networks are more prone to failures, and loss of access due to weak transmission power, terrain, interference, etc. Therefore, the reliability requirements of wireless networks should be rigorously assessed. However, the reliability issue for wireless networks is quite different from that for wired networks, as wireless networks introduce a unique feature called terminal mobility, in which the types & numbers of engaged components in end-to-end communications change from time to time.

The Object Management Group (OMG) has published a wireless Common Object Request Broker Architecture (CORBA) specification to provide wireless access & terminal mobility in CORBA [7], which we employ as a typical wireless network system to demonstrate our reliability analysis & evaluation

Manuscript received June 18, 2004. This work was supported by two grants, RGC Project no. CUHK4205/04E and UGC Project no. AoE/E-01/99, of the Hong Kong Special Administrative Region, China. Associate Editor: N. Ye.

The authors are with the Department of Computer Science and Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong (e-mail: xychen@cse.cuhk.edu.hk; lyu@cse.cuhk.edu.hk).

Digital Object Identifier 10.1109/TR.2005.847268

[1]The singular and plural of an acronym are always spelled the same.

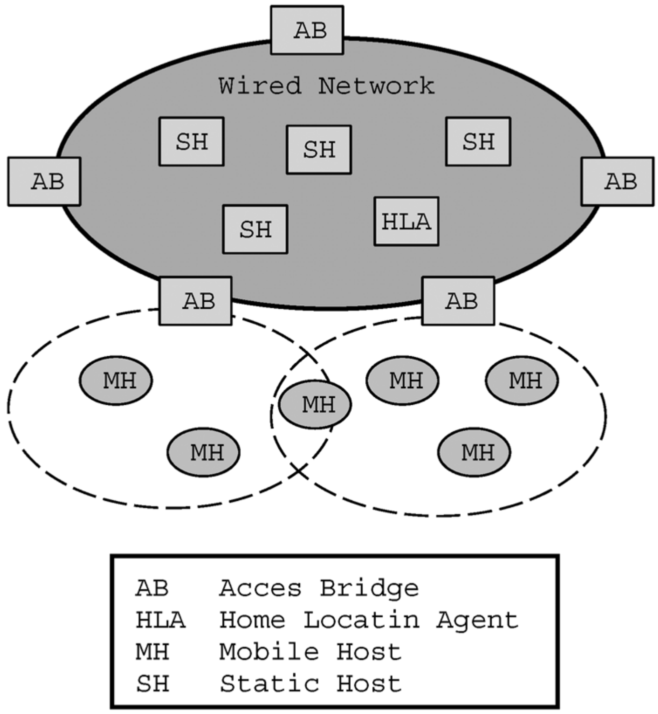

Fig. 1. The wireless CORBA architecture, and its components.

schemes. As shown in Fig. 1, a wireless CORBA environment consists of four main components excluding links:

- A mobile host (MH) is a terminal which accesses networks through a wireless network interface, and keeps network connections while roaming in wireless networks;
- A static host (SH) is a common & stationary node in wired networks;
- An access bridge (AB) is located between MH, and SH to relay messages for its associated MH. It is deployed in wired networks, but contains both wired & wireless network interfaces;
- A home location agent (HLA) keeps track of the locations of its registered MH, and provides operations to query an MH's location.

In wireless CORBA, an AB connects to the wired network from a fixed location using standard cabling. It receives, buffers, and transmits messages between the wired & wireless networks. A single AB supports a group of MH, functions within a certain radio transmission range, and provides a single cell of wireless coverage. Multiple AB provide multiple cells, allowing MH to roam from one cell to another while maintaining network connections. This cell roaming process is called *handoff*. MH communicate with each other only via their associated AB. No messages can be exchanged directly between MH, even if they stay in the same cell of an AB.

For a wireless CORBA network to be functional, its engaged components must be fit for service. Unfortunately, this is not always the case, because these components may suffer failures, and wired paths & wireless links may not be reliable. We need a mechanism to assess the reliability of wireless networks. However, because the wireless CORBA provides handoff operation, which is a new feature, the traditional two-terminal reliability defined in wired networks [8] is not suitable anymore. The handoff operation causes the existing communication structure to change with the MH's movement. At different time periods, different components are engaged in node-pair communications. This paper seeks a new approach to define the reliability metric in wireless networks, which not only keeps the monotonously decreasing characteristic of reliability but includes the mobility nature in the system. Different effects imposed by component failure parameters & mobile service parameters will be given through numerical examples. To observe the gain in reliability improvement, the reliability importance (RI) of imperfect components are also evaluated.

The remaining sections are organized as follows. Section II presents some related work in reliability evaluation & fault tolerance for wired & wireless networks. Section III defines the proposed end-to-end expected instantaneous reliability (EIR) & MTTF under some assumptions. Detailed descriptions & discussions for the end-to-end EIR in different communication schemes are provided in Section IV, and some remarks are given in Section V.

II. Related Work

Much work has been done in calculating, estimating, or bounding the reliability of a given wired network. One approach is by employing the combinatorics of network-reliability to produce lower & upper bounds with failure-prone links, but perfect nodes [4], [9]. Aggarwal *et al.* [1] developed a concept that the failure of a node implies the failure of links connecting it, with which a symbolic reliability expression derived with the assumption of perfect nodes could be directly modified to incorporate imperfect nodes. Torrieri [10] exploited a relation: the event of successful communication over a link is equivalent to the event that both the link & its terminal node are operational. Then he designed an efficient method to compensate for unreliable nodes in network-reliability computation, whose cost increases linearly with the number of links. Netes & Filin [11] added the imperfect nodes into paths for decomposing the network into an event-tree. Ke & Wang [2] partitioned the network into a set of smaller disjoint subnetworks to directly compute the network-reliability expression instead of using any compensating methods. Based on these previous bodies of work, here we also evaluate wireless network reliability with node failures by the introduced end-to-end EIR. However, we focus on various communication schemes instead of a static wired network topology. Their results could be employed into the end-to-end EIR to provide a more detailed & complete reliability assessment for wireless network systems.

Most recently, some work has been conducted in providing fault tolerance in wireless environments for reliability engineering. Fuchs & Neves [12] proposed a time-based checkpointing protocol to store consistent recoverable states of an application without message exchange. The protocol employs soft, and hard checkpoints to adapt to different characteristics of networks, and to provide differentiated recoveries. Park & Yeom [13] developed an asynchronous recovery scheme based on optimistic message logging in which the mobile support station (MSS) performs logging & dependency tracking.

Chen & Lyu [14] presented an approach engaging both quasisender-based, and receiver-based message logging methods; and achieving seamless handoff in the presence of failures in wireless CORBA. Alagra *et al.* [15] utilized pessimistic & optimistic replication strategies to tolerate MSS failures by making MH move to replicated MSS, or by designing a network to cover each MH with more than one MSS.

The analysis of performance & reliability issues in wireless networks has been addressed only by a handful of researchers. Pradhan *et al.* [16] discussed three checkpoint movement strategies to deal with the handoff issue: pessimistic, lazy, and trickle. They identified the optimal checkpointing interval, and concluded that the performance of a recovery scheme depends on the mobility of MH & the wireless bandwidth. The total program execution time under MH's failures & handoffs, and the effectiveness of checkpointing, were analyzed in [17]. Reliability & survivability issues of wireless networks were discussed in [18], which concluded that each component engaged in the end-to-end connection is a potential point of failure. However, it did not explicitly state how the user mobility, which is unique in wireless networks, affects the end-to-end reliability. Varshney *et al.* [19] modeled & simulated the reliability & survivability of infrastructure-oriented wireless networks with a proposed wireless infrastructure building-block (WIB). By scaling the number of WIB, they evaluated network failures & corresponding impacts under various observation durations, component failure characteristics, and network sizes. However, in this paper we attempt to extend the two-terminal reliability to embody the terminal mobility, and assess the network reliability by end-to-end successful communication. It is apparent that more research activities in investigating fault tolerance & reliability engineering techniques for wireless networks should be conducted.

III. Definitions and Assumptions

In general, reliability is defined as the probability that a system performs its intended functions successfully for a given period of time under specified environmental conditions [20], and we refer the probability of successful communication between a source node and a target node as *two-terminal reliability* [8]. For two nodes to communicate with each other, there should be at least one operating path connecting them. An operating path indicates that all the intermediate nodes & links should be in the operation state: a node is operational if, and only if, it functions as intended; and a link is operational if, and only if, it allows communication from its source node to its sink node [10]. Because the two-terminal reliability problem in wired networks has been studied thoroughly in the literature, we assume that the intermediate nodes & wired links are always reliable, i.e., there will always be a reliable wired path between an AB and an SH, or between an AB and another AB. For the wireless part, an MH constructs only one wireless link with one AB, and it is associated with only one AB at a time, except during a handoff operation. Therefore, the communication path built on the top of wireless links is simple, and we also assume that the wireless link failures are negligible. However, all the four components of wireless CORBA are failure-prone, and they may fail independently.

Based on the assumptions made before, a successful communication between two nodes is defined as the condition when all the engaged nodes, including the source node & the target node, are in the operational state. As a result, the SH-SH reliability is the multiplication between the two individual SH' reliabilities. If one or both of two terminals are MH, the traditional two-terminal reliability metric cannot correctly describe the characteristic introduced by the handoff operation. As MH move & perform handoff operations, the communication structures will vary with time t. Each communication structure can be regarded as a serial system composed of different types & numbers of engaged components. Additionally, the handoff operation induces that the MH's published address will be outdated, and a mechanism is needed to resolve the current location of the MH. Therefore, we propose a new term, end-to-end *Expected Instantaneous Reliability (EIR)* [21], to address these unique cases in wireless environments. We define a system state, s, as the communication structure; therefore, s changes with time t. Let $\pi_s(t)$ denote the probability that the system is in state s at time t. The end-to-end EIR at a generic time t, $ER(t)$, is given by

$$ER(t) = \sum_s \pi_s(t) R_s(t) \tag{1}$$

in which $R_s(t)$ denotes the reliability of the system in state s at time t. $R_s(t)$ can be expressed by

$$R_s(t) = \prod_{i=1}^{n(s)} R_i(t) = \prod_c \left[R_c(t)\right]^{n_c(s)} \tag{2}$$

in which $n(s)$, $n(s) = 2, 3, \ldots$, is the number of engaged components in system state s; $R_i(t)$ is the reliability of the i^{th} component; c is the type of a component, which may take a value of mh, ab, sh, or hla; and $n_c(s)$, $n_c(s) = 0, 1, 2, \ldots$, is the number of component c employed in state s. Here we have $n(s) = \sum_c n_c(s)$. $ER(t)$ is a function composed not only of failure parameters but also of service parameters introduced by state probability $\pi_s(t)$. The SH-SH reliability can be treated as a special case in which the system contains only one communication structure, i.e., $\pi_s(t) = 1$, and $ER_{ss}(t) = R_s(t) = [R_{sh}(t)]^2$. Under the adopted assumptions, we can say that the EIR is a generalization of the traditional two-terminal reliability. Accordingly, we define the corresponding end-to-end MTTF as

$$\text{MTTF} = \int_0^\infty ER(t) dt. \tag{3}$$

From the above definitions, we note that the end-to-end EIR can be easily extended to include the reliability metrics of wired networks & wireless links if we add the two-terminal reliability of wired networks, and the successful communication probability of wireless links, into the calculation of $R_s(t)$. However, these extensions only trivially decrease the derived value of EIR, but do not change the properties of EIR; for simplicity we omit them in this paper.

Four communication schemes will be generated if random communications occur between MH, and SH, which are the SS scheme, the MS scheme, the SM scheme, and the MM scheme. In these notations, the former capital letter denotes the type of

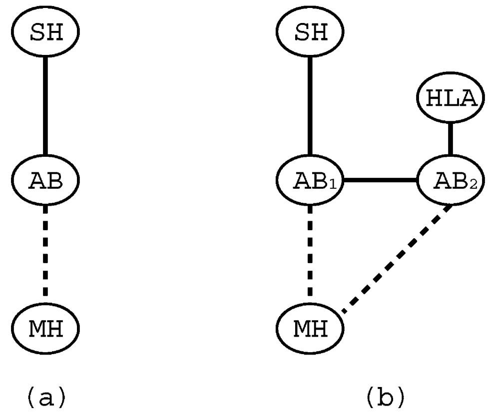

Fig. 2. System states in the MS scheme: (a) normal communication; (b) handoff procedure.

the source node, and the latter letter denotes the type of the target node, where M stands for MH, and S stands for SH.

During communications, an MH associates with an AB, and exchanges messages with other nodes. As the MH moves, it will make handoffs and associate with a new AB. The sojourn time with an AB, and the handoff completion time are assumed to be r.v. which are exponentially distributed with parameters ρ & η, respectively. We assume that the component hazard rates are constant. That is, we model component failures as homogeneous Poisson processes, resulting in independent & exponential inter-failure arrivals [19]. The constant failure parameters for the four components of wireless CORBA, MH, AB, SH, and HLA, are α, β, γ, and δ, respectively. We utilize the exponential distribution as the service & failure distributions for model simplicity. From the definition of EIR in (1), the EIR actually is a weighted value of reliabilities of different components. The derived properties of following discussions are only based on the monotonously decreasing characteristic of a reliability function with time, which is always the case; therefore, what the failure distribution really is should not affect the conclusions we will derive.

IV. End-to-End EIR & MTTF Analysis

Different communication schemes engage various types & numbers of components which result in different end-to-end EIR & MTTF. The SS scheme is trivial, and its EIR has been derived in the last section, i.e., $ER_{ss}(t) = [R_{sh}(t)]^2$. Therefore, we will discuss the remaining MS, SM, and MM schemes in the following three subsections separately.

A. The MS Scheme

The MS scheme is a communication scheme in which an MH initiates communications with an SH. Initially, the MH sends requests over a wireless link, then the associated AB relays the request messages to the target SH through wired paths. After a random sojourn time in the current AB, the MH may perform a handoff during which two AB are engaged. The system states are thus shown in Fig. 2, in which solid lines denote wired paths while dashed lines denote wireless links. State a is a normal communication state, and state b is a handoff state in which the

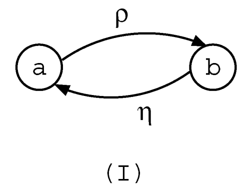

Fig. 3. Markov model for the MS scheme.

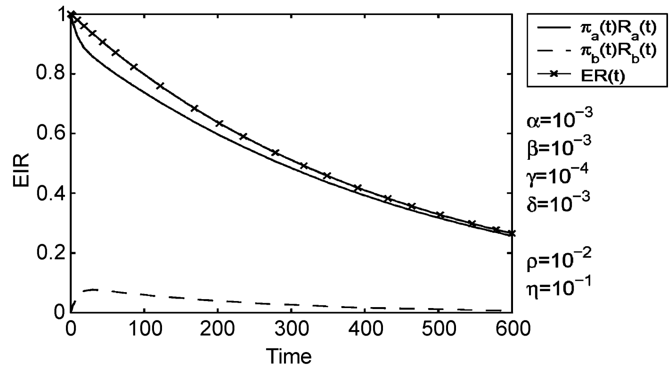

Fig. 4. EIR of the MS scheme.

MH moves from AB_1, to AB_2. The handoff may be network Initiated, or terminal initiated [7]; however, the engaged nodes, and links are the same. The MH should create two different wireless links with two AB, and these two AB should inform each other about the handoff progress. During handoff, the new AB, AB_2, should invoke the *location_update* operation at the MH's HLA to inform it that the MH has changed its associated AB. We may exclude the HLA from state b if we employ a simple invocation retry strategy, and the MH's location in the HLA will eventually be updated no matter whether the HLA works or not during the handoff. This is a simple extension to improve the system's reliability. After the handoff, the system returns to state a for normal communications. Fig. 3(I) shows the Markov model of the system state transition, where ρ is the handoff rate, and η is the handoff completion rate.

The probabilities of the system in states a & b, at time t can be solved analytically, which are given by [22]

$$\pi_a(t) = \frac{\eta}{\rho+\eta} + \frac{\rho}{\rho+\eta} \cdot e^{-(\rho+\eta)t} \tag{4}$$

and

$$\pi_b(t) = \frac{\rho}{\rho+\eta} - \frac{\rho}{\rho+\eta} \cdot e^{-(\rho+\eta)t} \tag{5}$$

respectively. One realization of the end-to-end EIR of the MS scheme, $ER_{ms}(t)$, is shown in Fig. 4.[2] Different types of components experience different levels of failures. SH are generally more reliable than MH or AB; therefore, we let $\alpha = \beta = 10^{-3}$, and $\gamma = 10^{-4}$ [16], [23]. We select the specific values of parameters for demonstrating the proposed end-to-end EIR, whereas these values are set at a reasonable & comparable level. As expected, the probability of the system in state a is much greater than that in state b as the handoff procedure is completed very

[2]The unit of all failure & service parameters is 1/s (one per second).

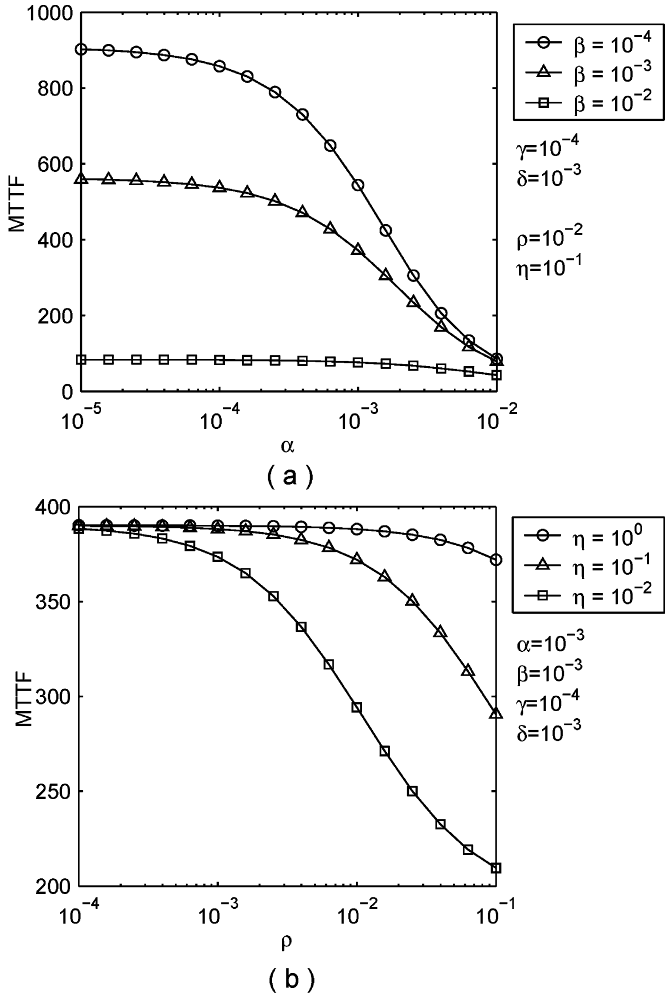

Fig. 5. End-to-end MTTF of the MS scheme: (a) failure parameters α & β; (b) service parameters ρ & η.

quickly, resulting in a case that the reliability of state a contributes much more to the EIR than that of state b. $R_b(t)$ is a monotonously decreasing function of time t; however, $\pi_b(t)$ increases first, and then approaches an upper limit. All these lead $\pi_b(t)R_b(t)$ to increase first, and then decrease. Nevertheless, the end-to-end EIR $ER(t)$ is still a monotonously decreasing function of time t. Fig. 5 shows the end-to-end MTTF as a function of failure & service parameters. The more reliable the components are, the longer the MTTF is. However, the improvement gain (in terms of the MTTF) reduces with the increase in the failure parameters, α & β, beyond a certain threshold, which can be observed from Fig. 5(a). Such diminishing gain should be carefully considered against the cost of increasing component reliabilities beyond a limit [19]. This result is also applied to parameter γ. From the following equation:

$$ER_{ms}(t) = \pi_a(t)e^{-(\alpha+\beta+\gamma)t} + \pi_b(t)e^{-(\alpha+2\beta+\gamma+\delta)t} \quad (6)$$

we see that α & γ produce the same effect on $ER_{ms}(t)$; and little difference exists between α and β when $\pi_b(t)$ is much smaller than $\pi_a(t)$. This means that each component is critical to successful system communications. The change of the failure rate of the HLA, δ, dose not make the MTTF demonstrate obvious variations, which implies that any gain by improving the reliability of the HLA will be small. This is because δ is only taken into consideration in state b, which does not contribute much to the EIR. Fig. 5(b) shows that when ρ is high, the MTTF increases with η dramatically; however, when ρ is low, the MTTF varies little with η. This indicates that when the handoff happens frequently, the time spent in the handoff period is very critical to the MTTF, because the reliability is clearly lower in the handoff state b than in the normal state a. When ρ is low, however, the contribution of the second term in (6) is small, leading to little change of the MTTF with η. To achieve a higher EIR, then, the MH experiencing high handoff rates should complete the handoff operation as fast as they can.

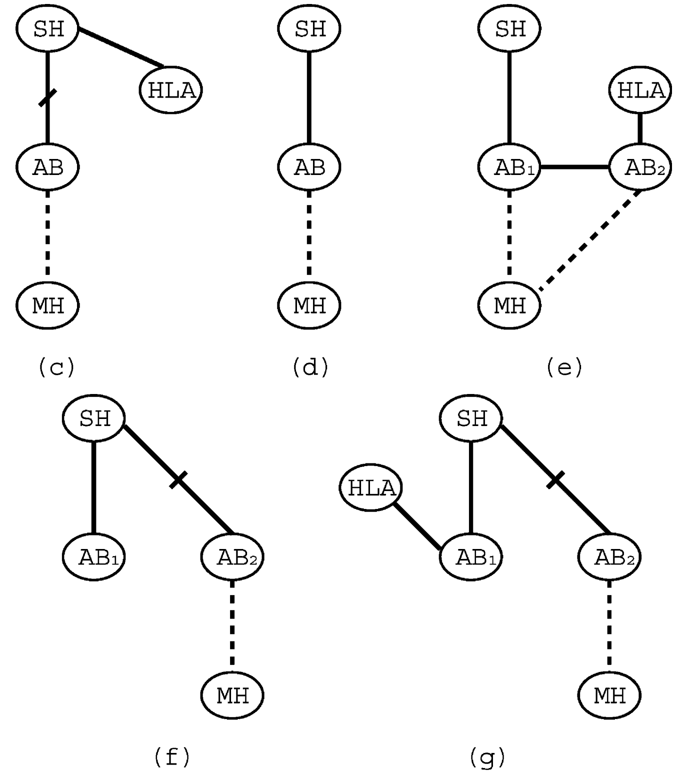

Fig. 6. System states in the SM scheme: (c) location-querying; (d) normal communication; (e) handoff procedure; (f and g) location-forwarding.

B. The SM Scheme

In the SM scheme, an SH initiates communications with an MH. The characteristic of an MH is its movement, which introduces a mechanism to locate its current AB. The location-lookup mechanism complicates the system states, as shown in Fig. 6. We know that an object on an MH publishes its Mobile Interoperable Object Reference (MIOR) with the address of its resided MH's HLA. When an SH first invokes an object on an MH with the originally published MIOR, the request message will be sent to the HLA indicated according to the address specified in the MIOR, and the HLA will send back a General Inter-ORB Protocol (GIOP) reply message with status *LOCATION_FORWARD*. This reply message carries a renewed MIOR containing the address of an AB with which the HLA believes the MH is currently associated [7]. This is

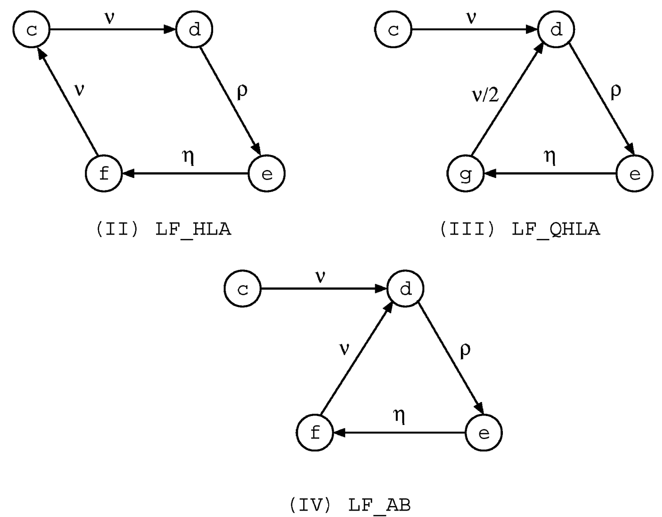

Fig. 7. Markov models for the SM scheme.

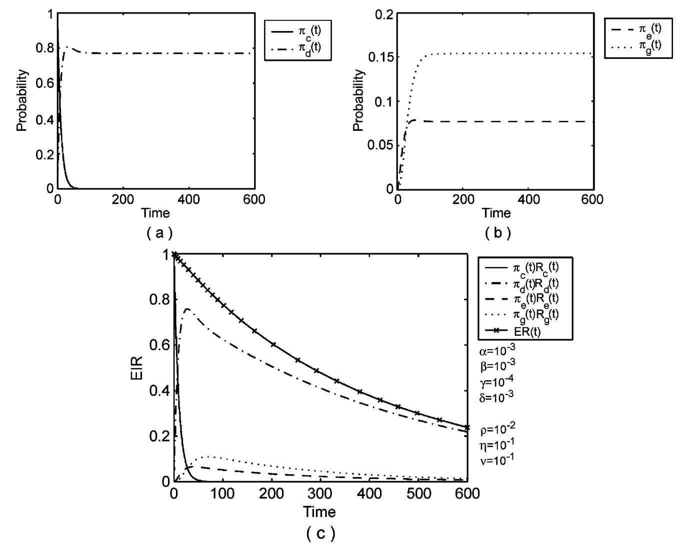

Fig. 8. State probabilities, and EIR of the SM scheme: (a) state probabilities of states c & d; (b) state probabilities of states e & g; (c) EIR.

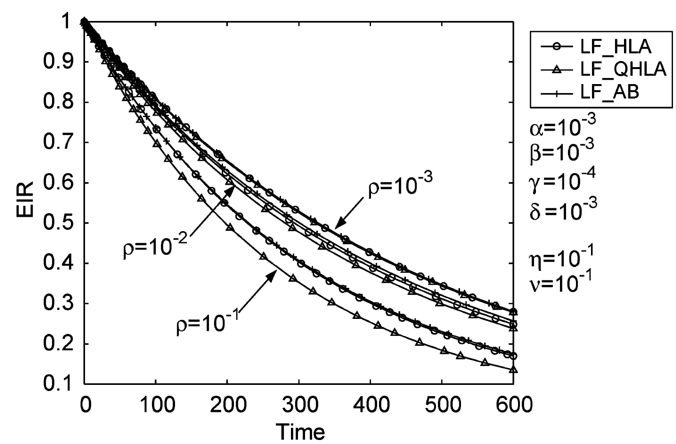

Fig. 9. EIR with location-forwarding strategies in the SM scheme.

state c, in which the solid line with slash indicates that the SH has not created a communication path with the AB; however, it is tending to construct such path with the AB. The time spent in this state is also assumed to be an exponentially distributed r.v. with parameter ν. The received LOCATION_FORWARD message directs the SH to reissue the request to the AB, and then the AB forward the message to the MH. This is state d. The system will stay in this normal communication state until the MH moves out of the coverage area of the current AB. State e is the handoff state. As the SH does not know whether or not its target MH has experienced a handoff, it still sends its subsequent requests to the known AB as normal despite the movement of the MH. However, when the AB receives a request, and finds that it has broken its link with the targeted MH, it will reply with a message whose status is also set to be LOCATION_FORWARD. There exist two ways to construct this reply message by replacing the address part in the Internet Inter-ORB Protocol (IIOP) profile of the MIOR with different addresses. One is the address of the MH's HLA, and the other is the address of the MH's current AB. We denote the former location-forwarding approach as *LF_HLA*, and the latter as *LF_QHLA*. Figs. (7II) & (III) show their corresponding Markov models, respectively.

In the LF_HLA approach, after handoff, the system moves from state e to state f, then to state c, resending the request to the HLA; however, the LF_QHLA approach changes state e to state g during which the AB queries the current location of the MH from its HLA. With the address of the new AB, the SH can reissue the request directly to the new AB, which results in the system transferring from state g directly to state d. The time spent in state f is also assumed to be an exponentially distributed r.v. with parameter ν because it functions as location-forwarding the same as state c. However, the transition rate from state g to state d should be different as state g engages one more operation than state f does. Here we set it to be $\nu/2$. The specific relationship between these two rates are not important here, but these two rates should not be independent. One more location-forwarding approach, denoted as *LF_AB*, could be engaged. Actually, the old AB knows to which AB the MH moves away from itself. If the MH does not leave the new AB when the old AB receives a request on this MH, the information in the old AB about the location of the MH is up-to-date, and it could be employed to construct the reply message. With this approach, the SH can still resend the request to the current AB; however, the location-querying operation in the LF_QHLA approach is removed. Its corresponding Markov model is shown in Fig. 7(IV).

The symbolic expression of the probabilities of the system in different states at time t are difficult to be derived. Therefore, we utilize a numerical approach here to express their variations with time t. Fig. 8 shows one realization for the LF_QHLA approach. The curve shapes of the other two approaches are similar to this one. We observe that the contribution of state c to the EIR decreases quickly as time moves on, because the probability of state c diminishes quickly. States d, e, and g exhibit similar behaviors in EIR as all these three states show similar curve shapes in state probability. When the decrease of the state reliability cancels out the increase of the state probability, the state's contribution to the EIR will start to decrease.

Fig. 9 shows the differences in EIR among these three location-forwarding approaches with various handoff rates. It is observed

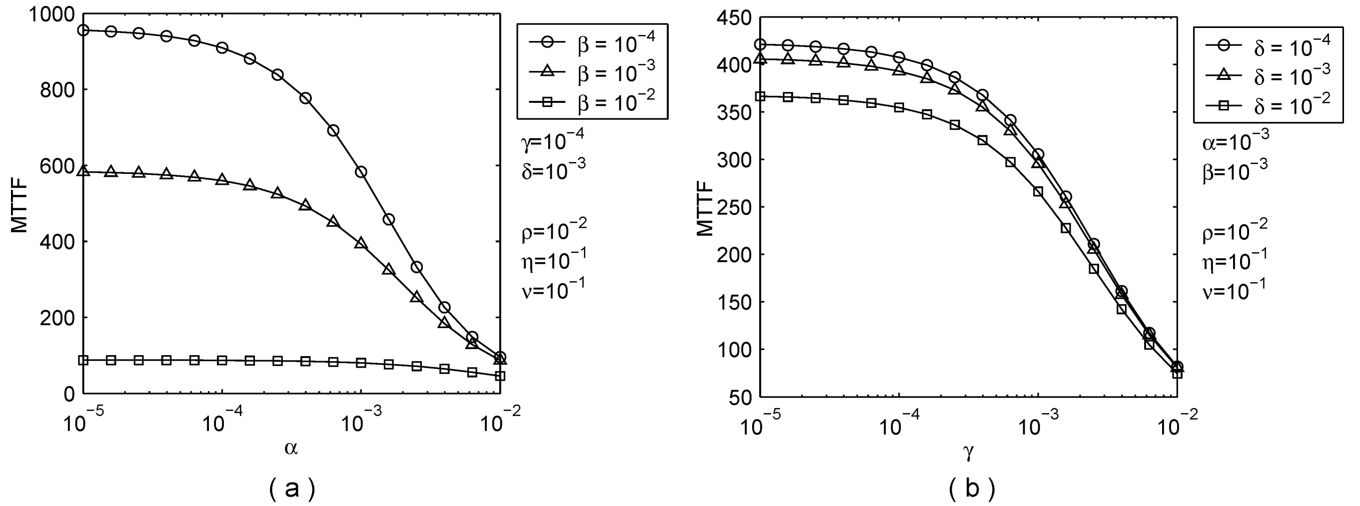

Fig. 10. End-to-end MTTF of the SM scheme vs. failure parameters: (a) α & β; (b) γ & δ.

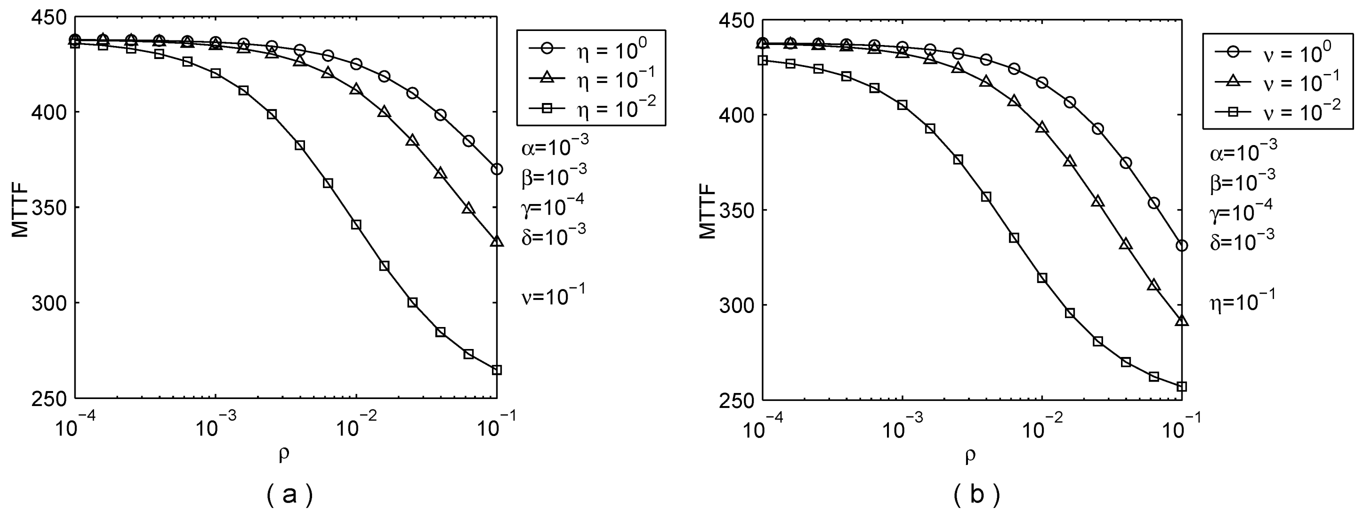

Fig. 11. End-to-end MTTF of the SM scheme vs. service parameters: (a) ρ & η; (b) ρ & ν.

that the proposed LF_AB approach achieves the highest EIR because it engages the least number of components, and finishes the location-forwarding procedure most quickly. However, these three approaches tend to behave the same when the handoff rate decreases. Another observation is that the LF_HLA approach is superior to the LF_QHLA approach. Although the LF_QHLA combines two states f & c into one state g, at the same time it introduces one more component, the HLA, into state g. This indicates that the number of engaged components during a communication state is more critical than the number of states.

How the MTTF varies with different parameters are shown in Figs. 10 & 11. We note that α, β, and γ produce similar effects on the MTTF of the SM scheme as those of the MS scheme. In Fig. 10(b), the decrease of δ also demonstrates an increase on the MTTF. This implies that the HLA plays a more important role in the SM scheme than in the MS scheme, although the improvement on the reliability of the HLA still achieves little increase on the MTTF compared with the improvement on other components. Finally, ν demonstrates the same behavior as η, as shown in Fig. 11(b), which indicates that the location-forwarding process should also be done as quickly as possible when ρ is high. However, when ρ is small, the improvement on the handoff completion & location-forwarding processes achieves little gain.

We have observed that the MH, and the AB behave almost the same in the improvement gain in terms of the MTTF in schemes MS & SM. Now we evaluate them from another point of view to see whether this result will be changed or not. We define *time-dependent RI* with respect to the EIR to identify the relative importance of each component in a system. The time-dependent RI, $I_{R_i}(t)$, of component i, $i = mh, ab, sh$, or hla, is given by

$$\begin{aligned} I_{R_i}(t) &= \frac{\partial ER(t)}{\partial R_i(t)} \\ &= \sum_s \pi_s(t) \cdot n_i(s) \big[R_i(t)\big]^{n_i(s)-1} \\ &\quad \cdot \prod_c \big[R_c(t)\big]^{n_c(s)} \quad c \neq i \end{aligned} \tag{7}$$

as we substitute $ER(t)$ with (1), and express $R_s(t)$ as $\prod_c [R_c(t)]^{n_c(s)}$. Applying (7) in the SM scheme, we show the results in Fig. 12. When the handoff rate is relatively high (Fig. 12(a) & (b)), the RI of the AB increases first, and then decreases, indicating the contribution of state e, f, or g is high. If the AB, and the MH experience the same failure rate (Fig. 12(a)),

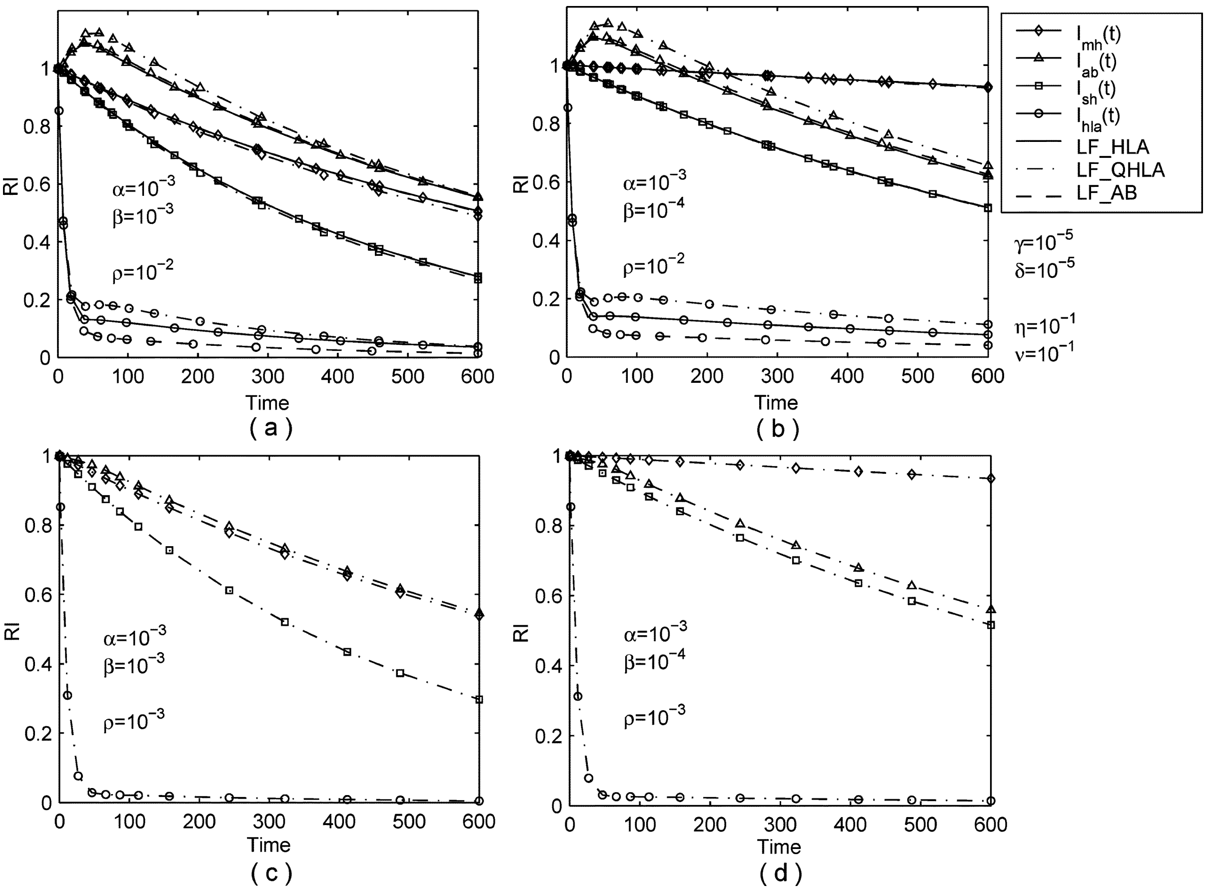

Fig. 12. RI of the SM scheme: (a) same failure rate, and high handoff rate; (b) different failure rates, and high handoff rate; (c) same failure rate, and low handoff rate; (d) different failure rates, and low handoff rate.

the AB always gets the higher RI than the MH does. On the other hand, if the AB is more reliable than the MH (Fig. 12(b)), the AB gets the higher RI initially, and then the MH gets the higher RI; otherwise, the MH always gets the higher RI with lower handoff rate (Fig. 12(d)).

These observations show that the relative RI of different components may vary with the intended working time of the system, and with the failure & service parameters. The RI of HLA & AB in the LF_QHLA approach are higher than those in the LF_HLA & LF_AB approaches. This is due to the larger sojourn probability in state g which incorporates both AB, and HLA. We compare the difference between Fig. 12(a) & (c), in which the AB & the MH inherit the same failure rate; so do the SH & the HLA. We only show the result of the LF_QHLA approach, as the other two behave almost the same. Even when AB & MH experience the same failure rate, the difference between their RI is relatively large when the handoff rate is relatively high; however, they get almost the same RI when the handoff rate is relatively low. The SH gets the higher RI than the HLA does despite the handoff rate. All these are induced by the probabilities of different system states in which each component engages. When the handoff rate is high, the system achieves greater probabilities in state e, f, or g, in which two AB are employed. Therefore, the RI of the AB will be higher than that of the MH. The SH is present in each system state, but the HLA does not appear in state c, which is the most important state. Obviously then, the RI of the SH should always be higher than that of the HLA.

C. The MM Scheme

The system becomes more complicated in the MM scheme as both MH may undergo handoffs, and the following location- forwarding approaches also increase the system states. Its system states are shown in Fig. 13. At first, the system is in state h, in which MH_1 is the invocation initiator, and MH_2 is the receiver. When MH_1 sends a request with the MIOR of an object on MH_2, its associated AB, AB_1, needs a location-forwarding approach to resolve the address of AB_2 in which MH_2 resides. Note that the renewed MIOR is only kept by AB_1, and MH_1 still keeps the original MIOR. After this step, AB_1 creates a communication path with AB_2, and then MH_1 sends messages to, and receives messages from, MH_2 through AB_1 & AB_2, without the interaction with the HLA. This is state i. States j & k denote the system states in which only one MH is in handoff. There exists a probability that both MH are in handoff, shown as state l. Here we assume that these two MH share one HLA, and do not reside within the same cell of an AB. These assumptions are reasonable because we could regard the derived results as the lower bounds, and the difference is small. Following state j, there are two possible transitions: one is to state l, and the other is to state h. State j cannot directly transit to state i, because after MH_1 moves to a new AB, this new AB does not contain any information about where MH_2 is, and thus it needs undergo state h to resolve the address of MH_2. There are also three location-forwarding approaches after the handoff completion of MH_2 in the

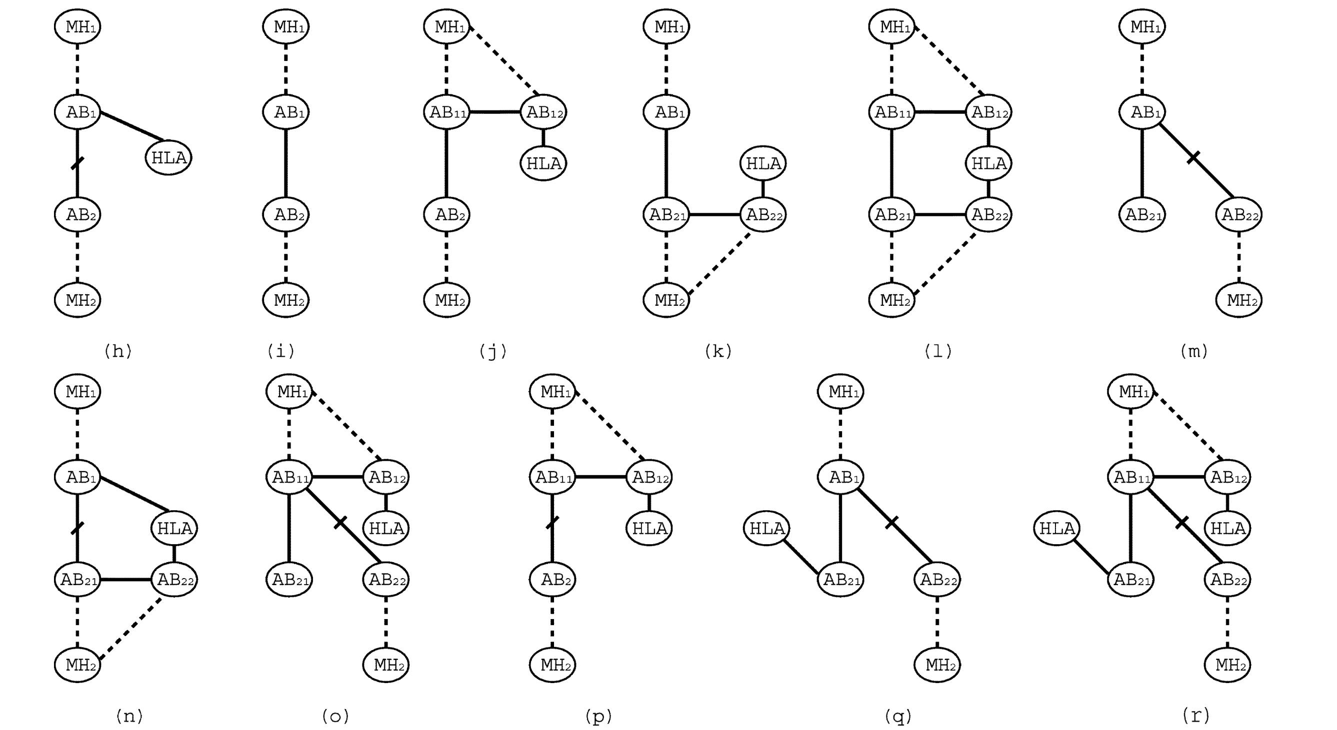

Fig. 13. System states in the MM scheme: (h) location-querying; (i) normal communication; (j) MH_1 in handoff; (k) MH_2 in handoff; (l) both MH_1 & MH_2 in handoff; (m & q) location-forwarding; (n) location-querying, and MH_2 in handoff; (o and r) location-forwarding, and MH_1 in handoff; and (p) location-querying, and MH_1 in handoff.

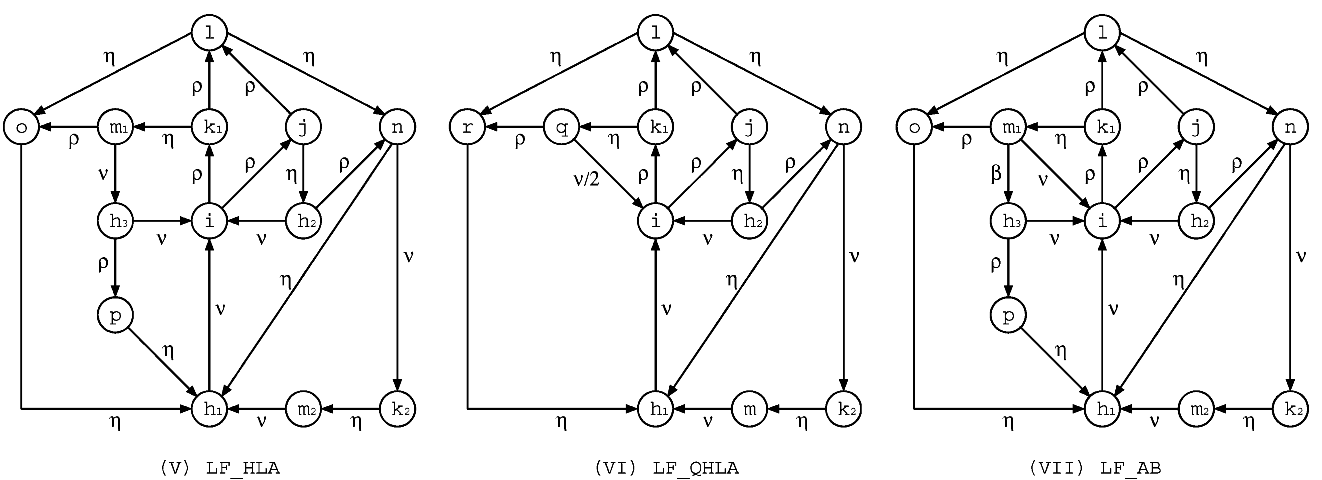

Fig. 14. Markov models for the MM scheme.

MM scheme, denoted as the same as in the SM scheme. For the LF_HLA approach, state m is the location-forwarding process after the handoff completion of MH_2 in state k. No matter which MH finishes its handoff first in state l, the system also enters the location-forwarding state, state n or o; however, entering which location-forwarding state depends on which MH completes its handoff earlier. From it we know that the location-forwarding approaches after the handoffs of MH_1 & MH_2 are different.

The corresponding Markov model for the LF_HLA approach is shown as Fig. 14(V), in which h_1, h_2, and h_3 represent the same communication structure as h while they represent different system states, the same denotations for k, and m. One more assumption has been made to draw this Markov model: before an MH makes another handoff, the location-forwarding process for its last handoff should have been finished. This assumption avoids creating an AB list in which the MH is moving to the header AB of this list while the location-forwarding procedure is being processed in the tail AB of this list. It is also feasible because the handoff rate is much less than the location-forwarding rate. With the LF_QHLA approach (Fig. 14(VI)), state q replaces state m, and it transits directly to state i instead of through state h_3. Correspondingly, state o is replaced by state r. Fig. 14(VII) is the Markov model for the LF_AB approach. We could make this approach more reliable by adding a transition from state m_1 to h_3 with rate β. Because AB_{21} functions as an HLA when the system is in state m, the HLA could be treated

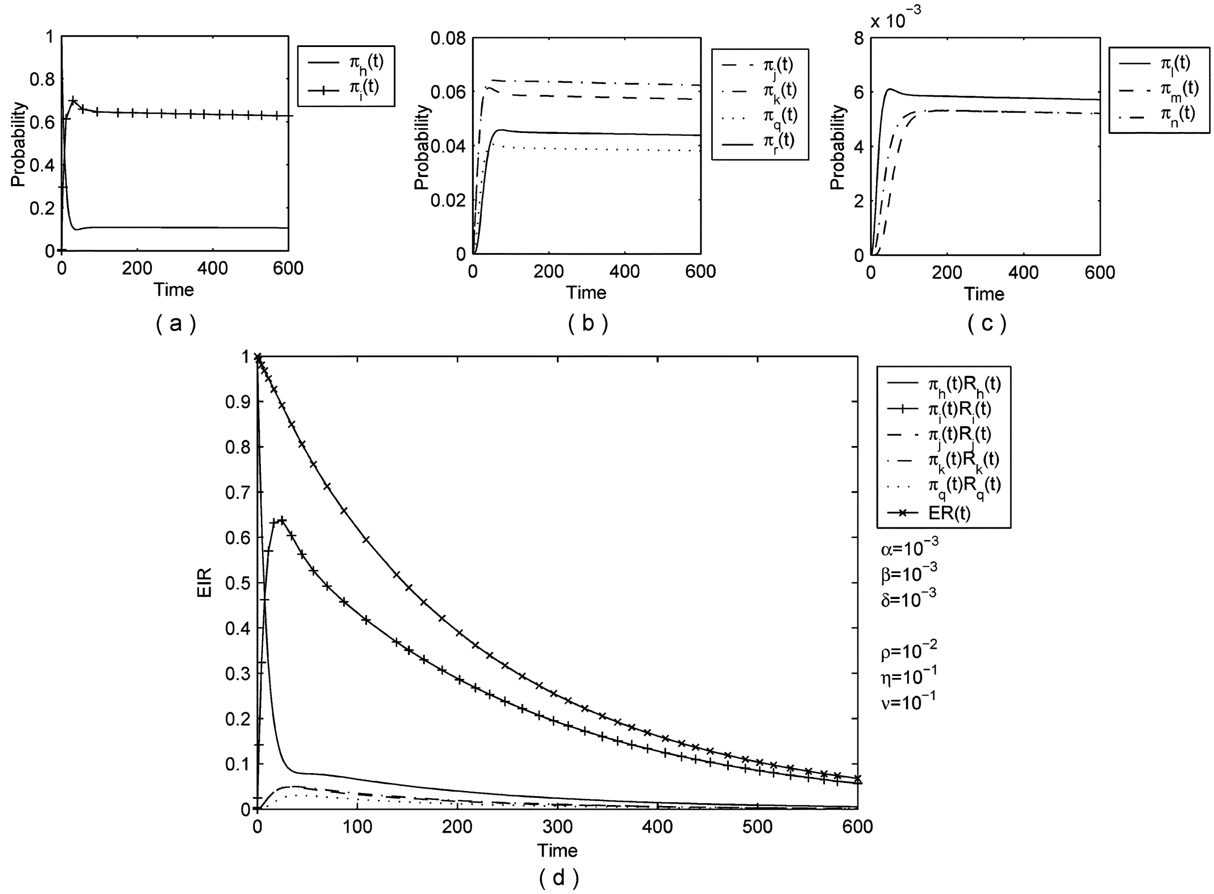

Fig. 15. State probabilities and EIR of the MM scheme: (a) state probabilities of states h, and i; (b) state probabilities of states j, k, q, and r; (c) state probabilities of states l, m, and n; (d) EIR.

as a hot standby component to replace AB_{21} when AB_{21} fails, even though the failure rates may be different between these two components. When AB_{21} fails to reply to a request, the AB_1 may reissue the request to the HLA to get the up-to-date MIOR. The wireless CORBA specification requires that only the ORB used to implement HLA & AB need to know the mobility of MH, therefore this proposed request-retry could only be employed in the MM scheme while it is not suitable for the SM scheme, otherwise the ORB in SH needs to be aware of terminal mobility.

The variations of the probabilities of system states with time t for the LF_QHLA approach are shown in Fig. 15 by employing that the system is initially in state h with probability 1. The probabilities of states j, k, q, and r are on one level of magnitude, and the probabilities of states l, m, and n are on another level of magnitude; however, all these states employ the same curve shape. Fig. 15(d) shows only some states' contributions to the EIR, and others are omitted for clarity. The effects of different parameters on the MTTF, and the RI, in the MM scheme are very similar to those analyzed & presented in the SM scheme, and thus are not included here.

D. General End-to-End MTTF

We have discussed the end-to-end MTTF with specific sender-receiver pairs in four communication schemes so far. Now we turn our attention to the general end-to-end MTTF of a wireless communication system which includes n_{mh} MH, and n_{sh} SH. If each MH or SH has the same probability to initiate a communication, then the general end-to-end MTTF can be expressed as

$$\mathrm{MTTF} = \frac{1}{2n_{mh}n_{sh} + \binom{n_{mh}}{2} + \binom{n_{sh}}{2}} \cdot \left[n_{mh}n_{sh} \cdot \mathrm{MTTF}_{ms} + n_{sh}n_{mh} \cdot \mathrm{MTTF}_{sm} + \binom{n_{mh}}{2} \cdot \mathrm{MTTF}_{mm} + \binom{n_{sh}}{2} \cdot \mathrm{MTTF}_{ss} \right] \quad (8)$$

in which we assume that all MH share a common HLA.

Fig. 16 shows how the general end-to-end MTTF varies with the number of nodes, in which the LF_QHLA approach is utilized for the SM & MM schemes. As expected, the MTTF decreases with the number of MH; however, it increases with the number of SH. The $MTTF_{sm}$ or $MTTF_{ms}$ is larger than the $MTTF_{mm}$ under the same parameter values as more components are engaged in the MM scheme. If the number of SH increases, an MH will communicate with an SH more probably; then the MTTF will become larger. The number of AB may also affect the MTTF because the MH needs AB to relay messages. According to our definition of the general end-to-end MTTF, however, the number of AB has no effect on it.

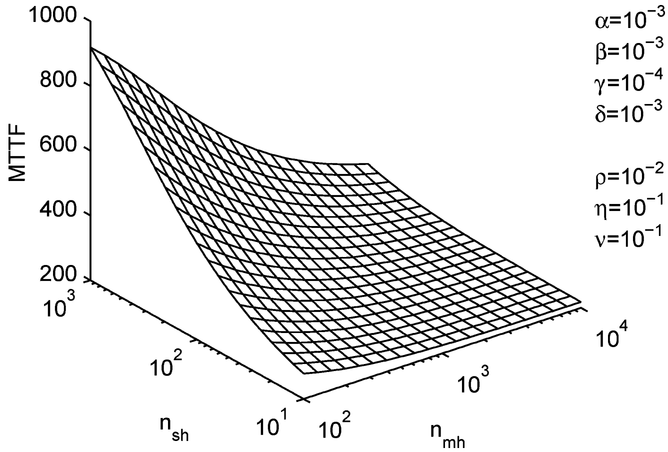

Fig. 16. General end-to-end MTTF vs. number of components.

V. Remarks

Four communication schemes have been discussed in this paper. No handoff operation is engaged in the SS scheme; as a result $ER_{ss}(t)$ is the traditional two-terminal reliability. For all other three schemes, MS, SM, and MM, the unique feature of wireless networks, handoff, is integrated into the expected instantaneous reliability. Quantitative measurements reveal that the handoff & location-forwarding procedures should be completed as soon as possible to improve the MTTF. Moreover, the RI of different components should be determined with specific failure & service parameters. Finally, the number of engaged components during a communication state is more critical than the number of system states.

References

[1] K. K. Aggarwal, J. S. Gupta, and K. B. Misra, "A simple method for reliability evaluation of a communication system," *IEEE Trans. Commun.*, vol. 23, no. 5, pp. 563–566, May 1975.

[2] W. J. Ke and S.-D. Wang, "Reliability evaluation for distributed computing networks with imperfect nodes," *IEEE Trans. Rel.*, vol. 46, no. 3, pp. 342–349, Sept. 1997.

[3] P. Kubat, "Estimation of reliability for communication/computer networks—simulation/analytic approach," *IEEE Trans. Commun.*, vol. 37, no. 9, pp. 927–933, Sept. 1989.

[4] S. M. Lee and D. H. Park, "An efficient method for evaluating network-reliability with variable link capacities," *IEEE Trans. Rel.*, vol. 50, no. 4, pp. 374–451, Dec. 2001.

[5] J. Shaio, "A family of algorithms for network reliability problems," in *Proc. of 2002 IEEE Int. Conf. Communications*, vol. 4, New York, Apr. 2002, pp. 2167–2173.

[6] R. B. Marks, I. C. Gifford, and B. O'Hara, "Standards in IEEE 802 unleash the wireless Internet," *IEEE Microwave Magazine*, vol. 2, no. 20, pp. 46–56, June 2001.

[7] *Wireless Access and Terminal Mobility in CORBA*, Object Management Group Std. 1.1, Apr. 2004.

[8] M. L. Shooman, *Reliability of Computer Systems and Networks: Fault Tolerance, Analysis, and Design*. New York: John Wiley & Sons Inc., 2002.

[9] F. M. Yeh, S.-K. Lu, and S.-Y. Kuo, "OBDD-based evaluation of k-terminal network reliability," *IEEE Trans. Rel.*, vol. 51, no. 4, pp. 443–451, Dec. 2002.

[10] D. Torrieri, "Calculation of node pair reliability in large networks with unreliable nodes," *IEEE Trans. Rel.*, vol. 43, no. 3, pp. 375–377, Sept. 1994.

[11] V. A. Netes and B. P. Filin, "Consideration of node failures in networkreliability calculation," *IEEE Trans. Rel.*, vol. 45, no. 1, pp. 127–128, Mar. 1996.

[12] W. K. Fuchs, N. Neves, and K. F. Ssu, "Dependable distributed and mobile computing—utilizing time to enhance recovery from failures," in *Dependable Network Computing*, D. R. Avresky, Ed: Kluwer Academic, 2000, ch. 14, pp. 315–339.

[13] T. Park and H. Y. Yeom, "An asynchronous recovery scheme based on optimistic message logging for the mobile computing systems," in *Proc. of the 20th Int. Conf. Distributed Computing Systems*, Taipei, Taiwan, Apr. 2000, pp. 436–443.

[14] X. Chen and M. R. Lyu, "Message logging and recovery in wireless CORBA using access bridge," in *Proc. of the 6th Int. Symp. Autonomous Decentralized Systems*, Pisa, Italy, Apr. 2003, pp. 107–114.

[15] S. Alagra, R. Rajagopalan, and S. Venkatesan, "Tolerating mobile support station failures," in *Proc. of the 1st Conf. on Fault Tolerant Systems*, Madras, India, Dec. 1995, pp. 225–231.

[16] D. K. Pradhan, P. Krishna, and N. H. Vaidya, "Recoverable mobile environment: design and trade-off analysis," in *Proc. of the 26th Int. Symp. on Fault-Tolerant Computing*, Sendai, Japan, June 1996, pp. 16–25.

[17] X. Chen and M. R. Lyu, "Performance and effectiveness analysis of checkpointing in mobile environments," in *Proc. of the 22nd Int. Symp. on Reliable Distributed Systems*, Florence, Italy, Oct. 2003, pp. 131–140.

[18] A. P. Snow, U. Varshney, and A. D. Malloy, "Reliability and survivability of wireless and mobile networks," *IEEE Computer*, vol. 33, no. 7, pp. 49–55, July 2000.

[19] U. Varshney, A. P. Snow, and A. D. Malloy, "Measuring the reliability and survivability of infrastructure oriented wireless networks," *Proc. of the 26th Ann. IEEE Conf. Local Computer Networks*, Tampa, Florida, Nov. 2001, pp. 611–618.

[20] R. Sahner, K. S. Trivedi, and A. Puliafito, *Performance and Reliability Analysis of Computer Systems—an Example Based Approach Using the SHARPE Software Package*. Boston: Kluwer Acadmedic Publishers, 1996.

[21] X. Chen and M. R. Lyu, "Expected-reliability analysis for wireless CORBA with imperfect components," in *Proc. of the 10th Pacific Rim Int. Symp. on Dependable Computing*, Tahiti, French Polynesia, Mar. 2004, pp. 207–215.

[22] W. Kuo and M. J. Zuo, *Optimal Reliability Modeling: Principles and Applications*, New Jersey: John Wiley & Sons Inc., 2003.

[23] I. R. Chen, B. Gu, S. George, and S.-T. Cheng, "On failure recoverability of client-server applications in mobile wireless environments," *IEEE Trans. Rel.*, 2004.

Xinyu Chen received the B.E. degree in mechanical engineering from Beijing Institute of Technology, Beijing, China, in 1997; and the M.E. degree in signal and information processing from Peking University, Beijing, China, in 2000. Now he is a Ph.D. candidate in the Department of Computer Science and Engineering at the Chinese University of Hong Kong, Hong Kong, China. His research interests include fault-tolerant distributed systems and mathematical modeling.

Michael R. Lyu (S'84–M'88–SM'97–F'04) received the B.S. degree in electrical engineering from National Taiwan University, Taipei, Taiwan, in 1981; the M.S. degree in computer engineering from University of California, Santa Barbara, in 1985; and the Ph.D. degree in computer science from University of California, Los Angeles, in 1988.

He is currently a Professor in the Department of Computer Science and Engineering, the Chinese University of Hong Kong. He is also Director of the Video over InternEt and Wireless (VIEW) Technologies Laboratory. He was with the Jet Propulsion Laboratory as a Technical Staff Member from 1988 to 1990. From 1990 to 1992, he was with the Department of Electrical and Computer Engineering, The University of Iowa, Iowa City, as an Assistant Professor. From 1992 to 1995, he was a Member of the Technical Staff in the applied research area of Bell Communications Research (Bellcore), Morristown, New Jersey. From 1995 to 1997, he was a Research Member of the Technical Staff at Bell Laboratories, Murray Hill, New Jersey. His research interests include software reliability engineering, distributed systems, fault-tolerant computing, mobile networks, Web technologies, multimedia information processing, and E-commerce systems. He has published over 200 refereed journal and conference papers in these areas. He received Best Paper Awards in ISSRE'98 and ISSRE'2003. He has participated in more than 30 industrial projects, and helped to develop many commercial systems and software tools. He was the editor of two book volumes: Software Fault Tolerance (New York: Wiley, 1995) and The Handbook of Software Reliability Engineering (Piscataway, NJ: IEEE and New York: McGraw-Hill, 1996).

Dr. Lyu initiated the First International Symposium on Software Reliability Engineering (ISSRE) in 1990. He was the program chair for ISSRE'96, and has served in program committees for many conferences, including ISSRE, SRDS, HASE, ICECCS, ISIT, FTCS, DSN, ICDSN, EUROMICRO, APSEC, PRDC, PSAM, ICCCN, ISESE, and WWW. He was the General Chair for ISSRE2001, and the WWW10 Program Co-Chair. He has been frequently invited as a keynote or tutorial speaker to conferences and workshops in U.S., Europe, and Asia. He served on the Editorial Board of IEEE Transactions on Knowledge and Data Engineering, and has been an Associate Editor of IEEE Transactions on Reliability and Journal Of Information Science And Engineering. Dr. Lyu is a Fellow of IEEE for his contribution to software reliability engineering and software fault tolerance.