Improving GSM Call Completion by Call Reestablishment

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***Abstract*— Global system for mobile communications (GSM) call reestablishment service allows a mobile station to resume a call in which the radio link has been temporarily interrupted due to interference or bad signal (which is referred to as an interrupted call). This service increases end user satisfaction and network quality perception. In this paper, we propose analytic models to study the performance for call reestablishment service. Our study indicates that call reestablishment can significantly reduces dropping for interrupted calls.**

***Index Terms*— Analytical model, call reestablishment, RES1 algorithm, RES2 algorithm, RES3 algorithm, simulation model.**

I. INTRODUCTION

PERSONAL communications services (PCS) networks provide telecommunications services to moving users. During a PCS communication session, a radio link is established between the mobile station (MS) and a base station (BS) if the MS is in the cell (the radio coverage area of the BS). If the MS moves to another cell during the conversation, then the radio link to the old BS is disconnected and a radio link to the new BS is required to continue the conversation. This process is called handoff [1], [2]. If the new BS does not have any idle channel, the handoff call is forced to terminate. Besides forced termination due to handoff, a radio link may be temporarily disconnected when propagation loss due to obstacle (e.g., bridges, tunnels) shielding. This phenomenon is referred to as "call interruption." To avoid forced termination due to call interruption, the call reestablishment service has been proposed in Global system for mobile communications (GSM) [4], [10]. In this mechanism, if a communication channel is interrupted, the network still reserves the trunk and/or the channel for the interrupted call, and an interruption timer is triggered. If the timer expires or the remote party hangs up the phone before the interruption period is over, the interrupted call is actually forced to terminate. Otherwise, the interrupted call is resumed by the call reestablishment mechanism. In this paper, we propose analytic and simulation models to evaluate the performance of GSM system with call reestablishment service.

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II. CALL REESTABLISHMENT MECHANISMS

This section describes three algorithms to reduce forced termination caused by interruption. Consider the timing diagram in Fig. 1(a). Suppose that a call alternates between the conversation periods and the interrupted periods. Define the ith cycle of a call as pair (x_i, y_i) where x_i is the ith conversation period and y_i is the ith interruption period. Every y_i is associated with a period z_i that denotes the interval between when the interruption begins and when the first of the following two events occurs: i) the interruption timer expires, and ii) the remote party hangs up the phone. For $k \geq 0$, let t_k be the holding time of the first k conversion cycles (i.e., $t_k = x_1 + y_1 + x_2 + y_2 + \cdots + x_k + y_k$). By convention, $t_0 = 0$. Let $t_{D,k} = t_k + x_{k+1}$. If the interrupted call is not resumed before the period z_i expires, the interrupted call is forced to terminate. Let τ_m be the period between the arrival of the call and when the MS enters the next cell (called cell 1), and $t_{m,0}$ be the cell residence time of the MS at cell 0. The three call reestablishment algorithms are: 1) RES1—the radio channel is reserved during interruption; the call is not reestablished if the MS moves into a new cell; 2) RES2—the radio channel is not reserved during interruption; the call is not reestablished if the MS moves into a new cell; and 3) RES3—the radio channel is reserved during interruption; the call is reestablished if the MS moves into a new cell. They are described as follows.

Algorithm RES1: For $k \geq 0$, consider the $k+1$st cycle of the call. There are five cases.

Case I: If $t_k < \tau_m < t_k + x_{k+1}$ [Fig. 1(b)], the MS moves to cell 1 during the conversation period. The call is handed off from cell 0 to cell 1 following the standard handoff procedure, and the call reestablishment mechanism is not triggered during handoff.

Case II: If $t_{D,k} + y_{k+1} \leq \tau_m$ and $y_{k+1} \leq z_{k+1}$ [Fig. 1(c)], then the call is reestablished at cell 0 after the MS leaves the shielding area.

Fig. 3 illustrates the messages exchanged between the MS and BS0 (the BS at cell 0): After interruption is over, the MS sends the call reestablishment request message to BS0 (message 1 in Fig. 3). The message contains the MS identification (ID) and the ID of the BS at which the call is interrupted (in this case, it is BS0). When BS0 receives the message, it checks the call record of the MS and stops the corresponding interruption timer. BS0 acknowledges the reestablishment request (message 2 in Fig. 3), and the call is reestablished.

Case III: If $t_{D,k} < \tau_m < t_{D,k} + y_{k+1}$ and $y_{k+1} \leq z_{k+1}$ [Fig. 2(a)], the interruption period ends before the interruption timer expires and the remote party does not hang up the phone.

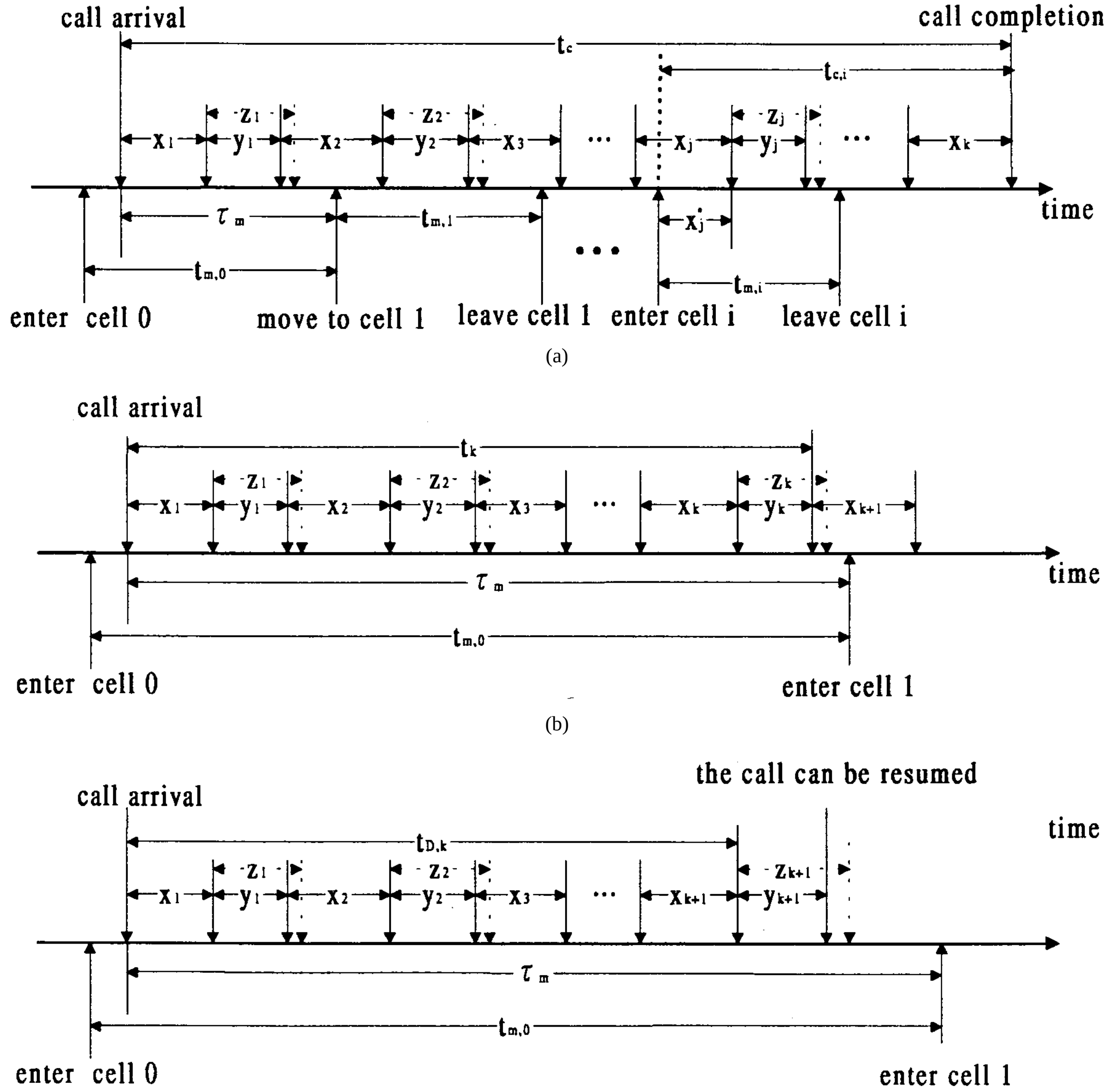


Fig. 1. Timing diagram I. (a) $x_i, y_i, z_i, t_c, t_{m,i}, \tau_m, t_{c,i}, x_j$, (b) Case I, and (c) Case II.

Since the MS enters cell 1 during the interruption period, the call is forced to terminate due to the fact that GSM follows the mobile assisted handoff strategy [2], [8]. In this case, BS0 will not release the reserved channel until the end of z_{k+1}. Note that the GSM mobile assisted handoff mechanism cannot perform radio link transfer if the MS fails to receive signal from the old cell (i.e., cell 0) during the handoff process.

Fig. 4 illustrates the message flow for this case. There are two possibilities: (a) The remote party hangs up the phone first, and (b) the interruption timer expires first.

Case IIIa: The remote party hangs up the phone before the interruption timer of BS0 expires. During the interruption period, the MS moves into cell 1. After the interruption, the MS sends BS1 the call reestablishment request message [see message 1 in Fig. 4(a)]. Since call interruption occurs at cell 0, BS1 cannot find the call record of the MS. BS1 replies a negative acknowledgment [see message 2 in Fig. 4(a)] that causes the call to be forced to terminate. Since $y_{k+1} < z_{k+1}$, BS0 still reserves the radio channel at this point. When the remote party hangs up the phone, the MSC cancels the call record of the MS, releases the trunk to the remote party, and sends a clear command message to BS0 [see message 3 in Fig. 4(a)]. After receiving the message, BS0 cancels the call record of the MS, releases the reserved channel for the interrupted call, and sends a clear complete message to the MSC [see message 4 in Fig. 4(a)].

Case IIIb: The interruption timer of BS0 expires before the remote party hangs up the phone. The first two messages delivered between the MS and BS1 are the same as those in Case IIIa [see messages 1 and 2 in Fig. 4(b)]. BS0 then sends a radio interface failure message to the MSC [see message 3 in Fig. 4(b)]. Based on the message, the MSC cancels the call record of the MS, releases the trunk to the remote party, and sends a clear command message to BS0 [see message 4 in Fig. 4(b)]. When BS0 receives the message, it cancels the call record of the MS, releases the reserved channel, and sends

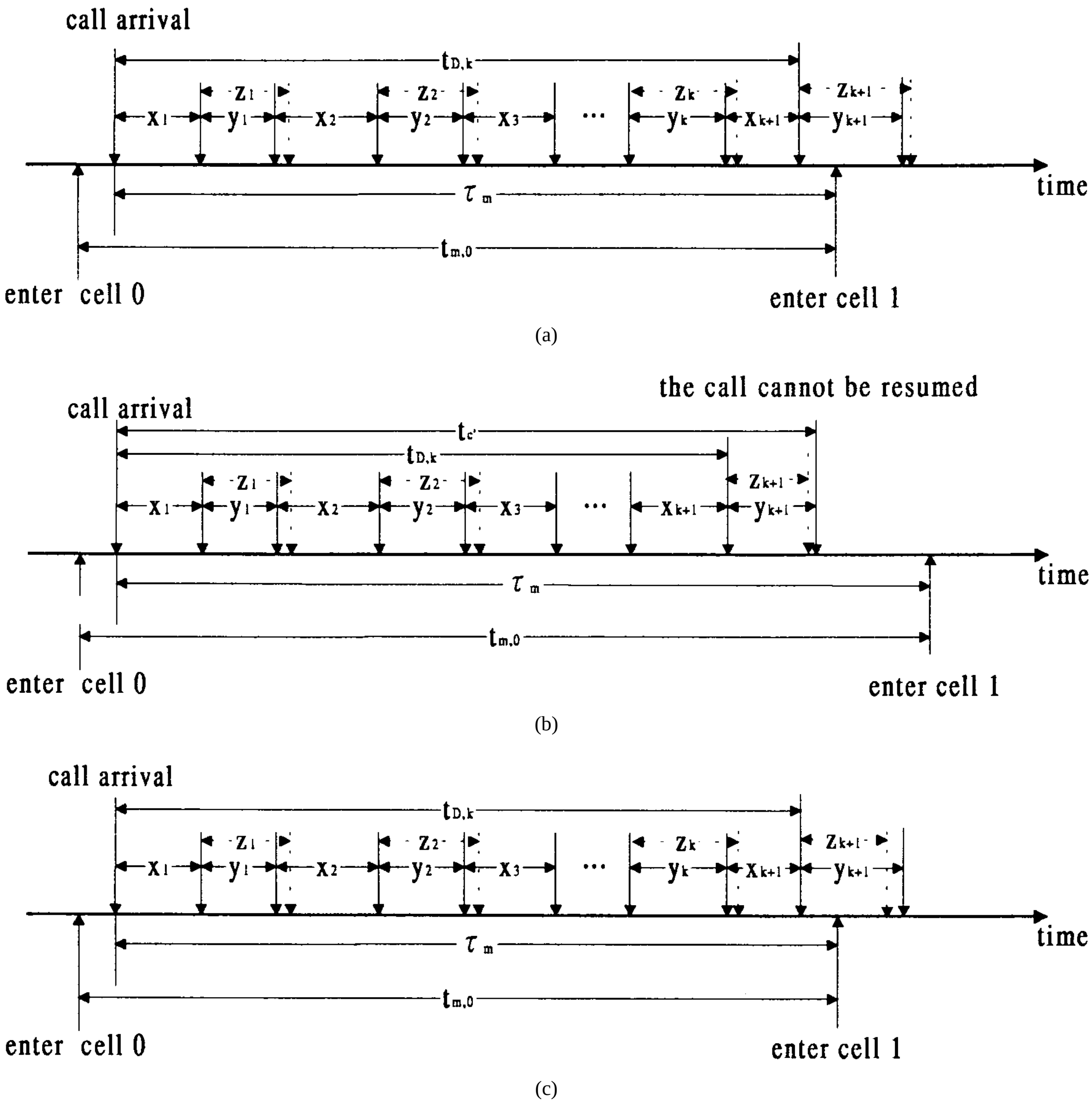


Fig. 2. Timing diagram II. (a) Case III, (b) Case IV, and (c) Case V.

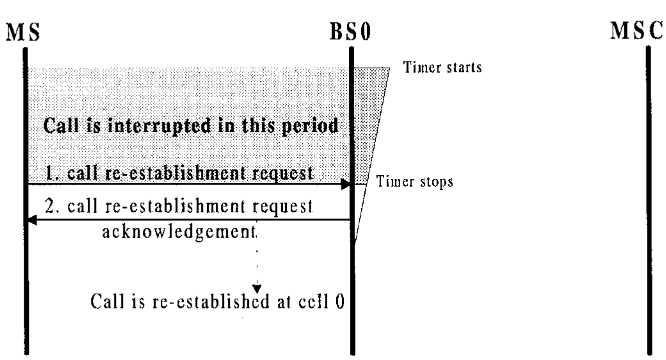


Fig. 3. Message flow for Case II of RES1.

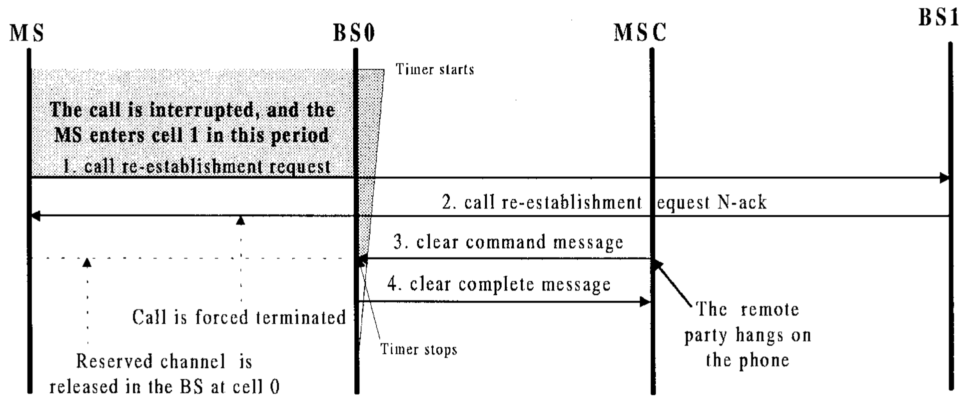
a clear complete message [see message 5 in Fig. 4(b)] to the MSC.

Note that messages 1 and 2 are not required in RES1. When the MS detects that it has moved to a new cell, it can terminate the call without exchanging these two messages. This message pair is required in RES3 to be described.

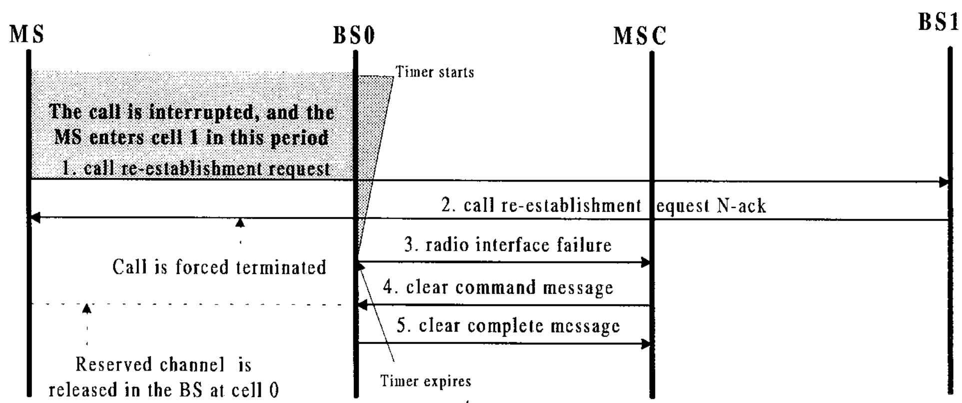
Case IV: If $t_{D,k} + y_{k+1} \leq \tau_m$ and $y_{k+1} > z_{k+1}$ [see Fig. 2(b)], the user hangs up the phone before the interruption period is over. In this case, the MS does not leave cell 0 during the interruption period. The call is dropped at cell 0, and BS0 releases the reserved channel after the interruption timer expires or when the remote party hangs up the phone.

The message flow for this case is similar to Case III, except that after the MS leaves the shielding area, it sends the call reestablishment request to BS0. Upon receipt of the message, BS0 finds that the call record of the MS does not exist. BS0 sends a negative acknowledgment to the MS, and the MS terminates the call.

Case V: If $t_{D,k} < \tau_m < t_{D,k} + y_{k+1}$ and $y_{k+1} > z_{k+1}$ [Fig. 2(c)], the interruption period ends after the interruption timer expires or after the remote party hangs up the phone. After the interruption, the MS is in cell 1, and the call is dropped as in Case III. In this case, BS0 releases the reserved channel when the interruption timer expires or after the remote



(a)



(b)

Fig. 4. Message flow for Case III of RES1. (a) The call is forced to terminate at cell 1, and the reserved channel is released by the MSC. (b) The call is forced to terminate at cell 1, and the reserved channel is released by BSO.

party hangs up the phone. The message flow for this case is the same as that in Case III.

To implement RES1, we only need to make minor modifications to the BS and MS. No changes are required in the MSC. In Figs. 3 and 4, the messages delivered between BS and MSC already exist in the current GSM implementation. In other words, there is no need to introduce new message types for the A interface [3] between the BS and MSC.

Algorithm RES2: RES2 is similar to RES1 except that as soon as the radio link between the MS and BS0 is interrupted, the BS0 releases the radio link. After interruption, the MS makes a call reestablishment request to the BS0. If BS0 has an idle channel, the interrupted call is reestablished. RES2 has been implemented in the existing Nortel GSM system [4], [10].

RES1 and RES2 fail to resume the interrupted call if the MS moves from cell 0 to cell 1 during interruption. To relax this restriction (i.e., to allow call reestablishment at cell 1), We extend RES1 as follows.

Algorithm RES3: RES3 allows a call to be reestablished after the MS moves to a new cell during interruption. For Cases I, II, and IV, the actions taken by RES3 are exactly the same as that in RES1. The actions for Cases III and V are described as follows.

Case III: If $t_{D,k}<\tau_m<t_{D,k}+y_{k+1}$ and $y_{k+1}\leq z_{k+1}$ [Fig. 2(a)], the MS enters cell 1 during the interruption period, and neither the interruption timer expires nor the remote party hangs up the phone during the interruption period. The MS makes a call reestablishment request to BS1. If BS1 has an idle channel, the call is reestablished.

Fig. 5 illustrates the message flow for Case III. After interruption, the MS sends the call reestablishment request message (see message 1 in Fig. 5) to BS1. On receipt of the message, BS1 forwards the call reestablishment request to the MSC (see message 2 in Fig. 5). The MSC checks the call record of the MS and sends a clear command message (see message 3 in Fig. 5) to BS0. BS0 stops the interruption timer, releases the reserved channel, and sends a clear complete message to the MSC (see message 4 in Fig. 5). The MSC sends a cipher mode command message (that contains the cipher info for the interrupted call; see message 5 in Fig. 5) to BS1. After receiving message 5, BS1 responds a cipher mode complete message (see message 6 in Fig. 5) to the MSC. The MSC then sends an assignment request message (see message 7 in Fig. 5) to BS1 to assign a channel to the interrupted call. BS1 queries the channel pool to find an idle channel for the interrupted call. If BS1 has idle channels, BS1 sends a assignment complete message to the MSC (see message 8 in Fig. 5) to indicate that BS1 is ready to accommodate the call transfer. The MSC sends a call reestablishment request acknowledgment to BS1 (see message 9 in Fig. 5), which is forwarded to the MS (see message 10 in Fig. 5). At this point, the call is reestablished at cell 1. Note that messages 5–8 are

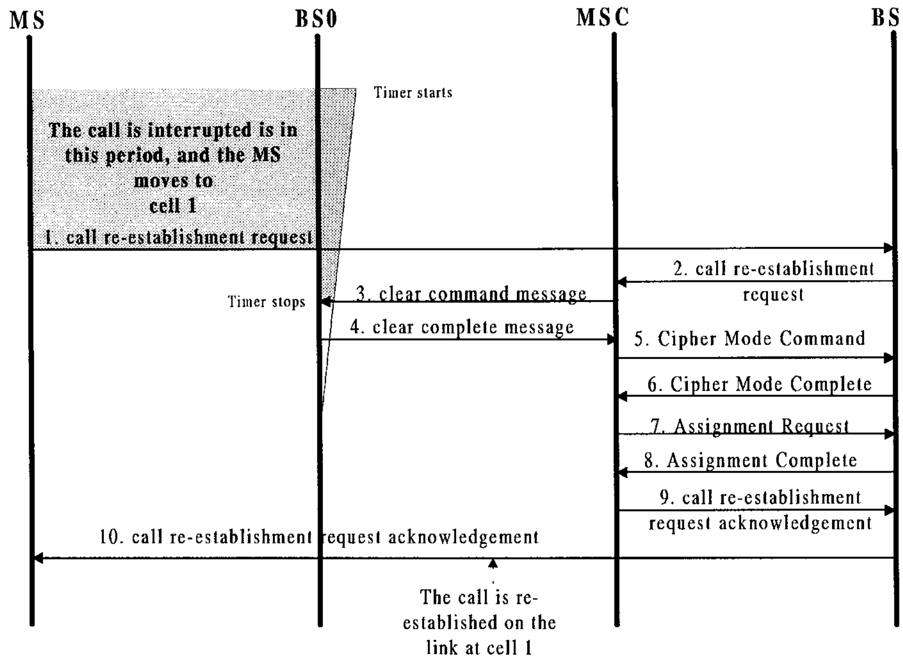


Fig. 5. Message flow for Case III of RES3.

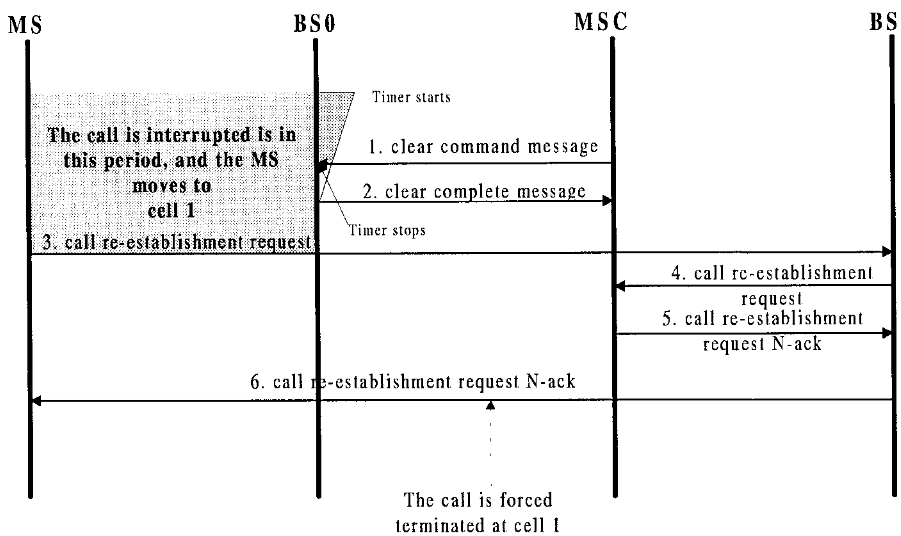


Fig. 6. Message flow for Case V of RES3.

standard GSM actions for link setup. For more details, the reader is referred to [4].

Case V: If $t_{D,k}<\tau_m<t_{D,k}+y_{k+1}$ and $y_{k+1}>z_{k+1}$ [see Fig. 2(c)], the call is forced to terminate at cell 1, and BS0 releases the reserved channel either when the interruption timer expires or when the remote party hangs up the phone.

Fig. 6 illustrates the message flow for this case. Period z_{k+1} expires before the interruption period ends. Thus, BS0 releases the reserved channel before the MS makes a call reestablishment request to BS1. The message flow for this action is the same as Case III in RES1. When interruption is over, the MS sends the call reestablishment request message to BS1 (see message 3 in Fig. 6). After receiving the message, BS1 forward the request to the MSC (see message 4 in Fig. 6). Since the MSC cannot find the call record for the MS (the MSC call record has been deleted after the BS interruption timer expired or after the remote party hung up the phone). The MSC replies a negative acknowledgment to BS1 (see message 3 in Fig. 6), which is forwarded to the MS (see message 4 in Fig. 6). At this point, the interrupted call is dropped in cell 1.

To implement RES3, modifications are made to the BS, MS, and MSC.

III. Analytic Models

We propose analytic models for GSM basic scheme (without call reestablishment), RES1 and RES3. The call incompletion probability P_{nc} is derived to investigate the performance of these algorithms. Call incompletion includes new call blocking and connected call dropping. This section describes the analytic models for RES1 and RES3. The model for

GSM basic scheme is similar to that for RES1 (but is less complicated) and is omitted.

A. An Analytic Model for RES1

Consider a cell in the GSM system. Let λ_o (λ_h) be the new (handoff) call arrival rate to the cell. Let P_b be the probability that all channels are busy when a call (either a new call or a handoff call) arrives. In GSM, the same channel assignment procedure is used for both the new calls and handoff calls. This nonprioritized scheme is considered in this paper. By using the techniques we proposed in [9], our model can be extended to study the case where the handoff calls have priority over the new calls. Let $P_{h,1}$ ($P_{h,2}$) be the probability that a connected new (handoff) call at the cell will hand off to the next cell. For a homogeneous cell structure (where the handoff rate entering the cell is equal to the handoff rate leaving the cell), we have

$$\lambda_h = \lambda_o(1-P_b)P_{h,1} + \lambda_h(1-P_b)P_{h,2}. \qquad (1)$$

Let $P_{i,1}$ ($P_{i,2}$) be the probability that a connected new (handoff) call at the cell will be disconnected due to interruption. As we described in Section III, a call alternates between the conversation periods and the interrupted periods. Assume that at the end of the conversation period x_i, the call is complete with probability $1-\alpha$, and with probability α, the radio channel is interrupted for a period y_i. If $y_i \leq z_i$, the call is reestablished and continues with the next conversation period x_{i+1}. Assume that x_i are independent, identically distributed (i.i.d.) random variables with the density function $\mu_x e^{-\mu_x x_i}$, y_i are i.i.d. random variables with the density function $\mu_y e^{-\mu_y y_i}$, and z_i are i.i.d. random variables with the density function $f_z(z_i)$, respectively. Exponential interruption periods are used in the analytic model to provide the mean value analysis. The effect of higher moments for general distribution can be studied in our simulation. Let β be the probability that a call is reestablished after interruption. Then

$$\begin{aligned}\beta &= \Pr[y_i \leq z_i]\\ &= \int_{z_i=0}^{\infty}\int_{y_i=0}^{z_i} \mu_y e^{-\mu_y y_i} f_z(z_i)\, dy_i\, dz_i\\ &= 1 - f_z^*(\mu_y)\end{aligned} \qquad (2)$$

where $f_z^*(s)$ is the Laplace transform of the z_i distribution. Let t_c be the call holding time of a complete call without considering the handoff effect [see Fig. 1(a)]. The density function $f_c(t_c)$ for t_c is

$$\begin{aligned}f_c(t_c) = \sum_{k=0}^{\infty} \Bigg[&\int_{x_1=0}^{t_c}\int_{y_1=0}^{t_c-x_1}\cdots\int_{y_k=0}^{t_c-x_1-y_1-\cdots-x_k}\\ &\times \alpha^k\beta^k(1-\alpha)\prod_{i=1}^{k}(\mu_x e^{-\mu_x x_i}\mu_y e^{-\mu_y y_i})\\ &\times \mu_x e^{-\mu_x(t_c-x_1-y_1-\cdots-x_k-y_k)} dy_k\cdots dx_1\Bigg].\end{aligned} \qquad (3)$$

From (3), the Laplace Transform of the t_c distribution is

$$\begin{aligned}f_c^*(s) &= \sum_{k=0}^{\infty}\left[\frac{\alpha\beta\mu_x\mu_y}{(s+\mu_x)(s+\mu_y)}\right]^k\left[\frac{(1-\alpha)\mu_x}{s+\mu_x}\right]\\ &= \frac{(1-\alpha)\mu_x(s+\mu_y)}{(s+\mu_x)(s+\mu_y)-\alpha\beta\mu_x\mu_y}.\end{aligned} \qquad (4)$$

Let t_k be the holding time for the first k cycles of a call [see Fig. 1(b)]. The density function $f_k(t_k)$ of t_k (without considering handoff) is expressed as

$$f_k(t_k) = \begin{cases} 0, & \text{if } k=0\\ \int_{x_1=0}^{t_k}\int_{y_1=0}^{t_k-x_1}\cdots\int_{x_k=0}^{t_k-x_1-y_1-\cdots-x_{k-1}-y_{k-1}} & \\ \int_{y_k=0}^{t_k-x_1-y_1-\cdots-y_k-x_k} \alpha^k\beta^k\prod_{i=1}^{k}(\mu_x e^{-\mu_x x_i}\mu_y e^{-\mu_y y_i}) & \\ dy_k\, dx_k\cdots dy_1\, dx_1, & \text{if } k>0\end{cases} \qquad (5)$$

and its Laplace Transform is

$$f_k^*(s) = \left[\frac{\alpha\mu_x\beta\mu_y}{(s+\mu_x)(s+\mu_y)}\right]^k. \qquad (6)$$

The residence time of the MS at cell i (the time interval that the MS stays in cell i) is $t_{m,i}$ [see Fig. 1(a)]. For all $i \geq 1$, $t_{m,i}$ are assumed to be i.i.d. random variables with the density function $f_m(t_{m,i}) = \eta e^{-\eta t_{m,i}}$. Suppose that a call arrives when the MS is in cell 0. Let τ_m be the period between the arrival of the call and when the MS moves out of cell 0. In our study, the cells are numbered 0, 1, 2, ..., in the order they are visited by the MS. Let $r_m(\tau_m)$ be the density function of τ_m with the Laplace transform $r_m^*(s)$. The probability $P_{h,1}$ is derived as follows:

$$\begin{aligned}P_{h,1} &= \Pr[\text{Case I in RES1 occurs}]\\ &= \sum_{k=0}^{\infty}\Pr[t_k < \tau_m < t_k + x_{k+1}]\\ &= \sum_{k=1}^{\infty}\Bigg[\int_{t_k=0}^{\infty}\int_{\tau_m=t_k}^{\infty}\int_{x_{k+1}=\tau_m-t_k}^{\infty}\\ &\qquad \times f_k(t_k)r_m(\tau_m)\mu_x e^{-\mu_x x_{k+1}}\, dx_{k+1}\, d\tau_m\, dt_k\Bigg]\\ &\quad + \int_{\tau_m=0}^{\infty}\int_{x_1=\tau_m}^{\infty} r_m(\tau_m)\mu_x e^{-\mu_x x_1}\, dx_1\, d\tau_m\\ &= \sum_{k=1}^{\infty}\Bigg[\int_{t_k=0}^{\infty}\int_{\tau_m=t_k}^{\infty} f_k(t_k)r_m(\tau_m)e^{-\mu_x(\tau_m-t_k)}\\ &\qquad \times d\tau_m dt_k\Bigg] + \int_{\tau_m=0}^{\infty} r_m(\tau_m)e^{-\mu_x\tau_m}\, d\tau_m.\end{aligned} \qquad (7)$$

Since $f_m(t_{m,i}) = \eta e^{-\eta t_{m,i}}$, from the excess life theorem [6],

$r_m(\tau_m) = \eta e^{-\eta\tau_m}$ and (7) is rewritten as

$$P_{h,1} = \sum_{k=1}^{\infty}\left[\int_{t_k=0}^{\infty}\int_{\tau_m=t_k}^{\infty} f_k(t_k)\eta e^{-\eta\tau_m}e^{-\mu_x(\tau_m-t_k)} \times d\tau_m\, dt_k\right] + \int_{\tau_m=0}^{\infty}\eta e^{-(\eta+\mu_x)\tau_m}\, d\tau_m = \left(\frac{\eta}{\eta+\mu_x}\right)\left[\sum_{k=0}^{\infty} f_k^*(\eta)\right] = \frac{\eta(\eta+\mu_y)}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y}. \quad (8)$$

The probability $P_{i,1}$ is derived as follows. Consider Case IV in RES1. Let $t_{c'} = t_{D,k}+y_{k+1}$ and $y_{k+1} > z_{k+1}$ [see Fig. 2(b)]. Then the density function $f_{c'}(t_{c'})$ is

$$f_{c'}(t_{c'}) = \sum_{k=0}^{\infty}\left[\int_{x_1=0}^{t_{c'}}\int_{y_1=0}^{t_{c'}-x_1}\cdots\int_{y_{k-1}=0}^{t_{c'}-x_1-y_1-\cdots-x_{k+1}} \times \alpha^{k+1}\beta^k(1-\beta)\prod_{i=1}^{k}(\mu_x e^{-\mu_x x_i}\mu_y e^{-\mu_y y_i}) \times \mu_x e^{-\mu_x x_{k+1}}\mu_y e^{-\mu_y(t_{c'}-x_1-y_1-\cdots-x_{k+1})} \times dx_{k+1}\cdots dx_1\right] \quad (9)$$

and its Laplace transform is

$$f_{c'}^*(s) = \frac{\alpha\mu_x(1-\beta)\mu_y}{(s+\mu_x)(s+\mu_y)-\alpha\beta\mu_x\mu_y}. \quad (10)$$

From (10), the probability of Case IV in RES1 is derived as

$$\Pr[\text{Case IV in RES1 occurs}] = \Pr[t_{c'} \le \tau_m] = \int_{\tau_m=0}^{\infty}\int_{t_{c'}=0}^{\tau_m}\eta e^{-\eta\tau_m} f_{c'}(t_{c'})\, dt_{c'}\, d\tau_m = \frac{\alpha\mu_x(1-\beta)\mu_y}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y}. \quad (11)$$

Consider Cases III and V in RES1 [see Fig. 2(a) and (c)]. The density function $f_{D,k}(t_{D,k})$ of $t_{D,k}$ is expressed as

$$f_{D,k}(t_{D,k}) = \begin{cases} \mu_x e^{-\mu_x t_{D,k}}, & \text{if } k=0 \\ \int_{x_1=0}^{t_{D,k}}\int_{y_1=0}^{t_{D,k}-x_1}\cdots \times\int_{x_{k+1}=0}^{t_{D,k}-x_1-y_1-\cdots-x_{k-1}-y_{k-1}} \alpha^{k+1}\beta^k \times\prod_{i=1}^{k}(\mu_x e^{-\mu_x x_i}\mu_y e^{-\mu_y y_i}) \times\mu_x e^{-\mu_x x_{k+1}} dx_{k+1}\, dy_k\, dx_k\cdots dy_1\, dx_1, & \text{if } k>0 \end{cases} \quad (12)$$

and its Laplace transform is

$$f_{D,k}^*(s) = \left[\frac{\alpha\beta\mu_x\mu_y}{(s+\mu_x)(s+\mu_y)}\right]^k\left(\frac{\alpha\mu_x}{s+\mu_x}\right). \quad (13)$$

We have

$$\begin{aligned}\Pr&[\text{Case III or V in RES1 occur}] \\ &= \Pr[t_{D,k} < \tau_m < t_{D,k}+y_{k+1}] \\ &= \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty}\int_{\tau_m=t_{D,k}}^{\infty}\int_{y_{k+1}=\tau_m-t_{D,k}}^{\infty} f_{D,k}(t_{D,k}) \times r_m(\tau_m)\mu_y e^{-\mu_y y_{k+1}} dy_{k+1}\, d\tau_m\, dt_{D,k}\right] \\ &= \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty}\int_{\tau_m=t_{D,k}}^{\infty} \times f_{D,k}(t_{D,k})r_m(\tau_m)e^{\mu_y(\tau_m-t_{D,k})}d\tau_m dt_{D,k}\right] \\ &= \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty} f_{D,k}(t_{D,k})\left(\frac{\eta}{\eta+\mu_y}\right)e^{-\eta t_{D,k}}\, dt_{D,k}\right] \\ &= \left(\frac{\eta}{\eta+\mu_y}\right)\left[\sum_{k=0}^{\infty} f_{D,k}^*(\eta)\right] \\ &= \frac{\alpha\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y}. \quad (14)\end{aligned}$$

Since Cases IV, III, and V in RES1 will drop the call, from (11) and (14), we have

$$\begin{aligned}P_{i,1} &= \Pr[\text{Case IV in RES1 occurs}] + \Pr[\text{Case III or V in RES1 occurs}] \\ &= \frac{\alpha\mu_x(1-\beta)\mu_y}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} + \frac{\alpha\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y}. \quad (15)\end{aligned}$$

Similarly

$$P_{h,2} = \frac{\eta(\eta+\mu_y)}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} \quad (16)$$

and

$$P_{i,2} = \frac{\alpha\mu_x(1-\beta)\mu_y}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} + \frac{\alpha\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y}. \quad (17)$$

Consider an observation period $\triangle t$. During this period, there are $\lambda_o\triangle t$ new call arrivals to a cell. These new calls generate $\lambda_h\triangle t$ handoff calls. From the homogeneous cell structure, the rate of handoff calls leaving this cell equals the handoff rate flowing into the cell. Among the new and the handoff call arrivals, $(1-P_b)P_{i,1}\lambda_o\triangle t$ new calls and $(1-P_b)P_{i,2}\lambda_h\triangle t$ handoff calls will be forced to terminate due to interruption. Thus, the number of blocked calls at the cell is $P_b\lambda_o\triangle t +$

$P_b\lambda_h\Delta t + (1-P_b)P_{i,1}\lambda_o\Delta t + (1-P_b)P_{i,2}\lambda_h\Delta t$, and the incompletion probability P_{nc} is expressed as

$$\begin{aligned} P_{nc} &= \frac{P_b\lambda_o\Delta t + P_b\lambda_h\Delta t}{\lambda_o\Delta t} \\ &\quad + \frac{(1-P_b)P_{i,1}\lambda_o\Delta t + (1-P_b)P_{i,2}\lambda_h\Delta t}{\lambda_o\Delta t} \\ &= P_b + \frac{\lambda_h}{\lambda_o} P_b + (1-P_b)P_{i,1} + \frac{\lambda_h}{\lambda_o}(1-P_b)P_{i,2}. \end{aligned} \tag{18}$$

Let t_{cn} be the channel occupation time of a new call that is either complete in a cell or handed off to the next cell. The expected value $E[t_{cn}]$ is derived as follows:

$$\begin{aligned} E[t_{cn}] &= E[t_c \text{ where } \tau_m > t_c] \\ &\quad + E[\tau_m \text{ where for all } k \geq 0, t_k < \tau_m < t_k + x_{k+1}] \end{aligned} \tag{19}$$

where

$$\begin{aligned} E[t_c \text{ where } \tau_m > t_c] &= \int_{t_c=0}^{\infty}\int_{\tau_m=t_c}^{\infty} t_c\eta e^{-\eta\tau_m} f_c(t_c)d\tau_m dt_c \\ &= \int_{t_c=0}^{\infty} t_c f_c(t_c)e^{-\eta t_c}dt_c \\ &= -\frac{d}{ds}f_c^*(s)\Big|_{s=\eta} \\ &= \frac{(1-\alpha)\mu_x(\eta+\mu_x)(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad - \frac{(1-\alpha)\mu_x}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} \end{aligned} \tag{20}$$

and

$$\begin{aligned} &E[\tau_m \text{ where for all } k, t_k < \tau_m < t_k + x_{k+1}] \\ &\quad = \sum_{k=0}^{\infty}\left[\int_{t_k=0}^{\infty}\int_{\tau_m=t_k}^{\infty}\int_{x_{k+1}=\tau_m-t_k}^{\infty} \tau_m f_k(t_k)\eta e^{-\eta\tau_m} \right. \\ &\quad\quad \left. \times\ \mu_x e^{-\mu_x x_{k+1}}\, dx_{k+1}\, d\tau_m\, dt_k\right] \\ &\quad = \sum_{k=0}^{\infty}\left\{\int_{t_k=0}^{\infty} f_k(t_k)\eta e^{\mu_x t_k} \right. \\ &\quad\quad\quad \left. \times \left[\int_{\tau_m=t_k}^{\infty} \tau_m e^{-(\eta+\mu_x)\tau_m}\, d\tau_m\right] dt_k\right\} \\ &\quad = \sum_{k=0}^{\infty}\left\{\left(\frac{\eta}{\eta+\mu_x}\right)\left[\int_{t_k=0}^{\infty} t_k f_k(t_k)e^{-\eta t_k}dt_k\right] \right. \\ &\quad\quad \left. + \left[\frac{\eta}{(\eta+\mu_x)^2}\right]\left[\int_{t_k=0}^{\infty} f_k(t_k)e^{-\eta t_k}\, dt_k\right]\right\} \\ &\quad = \sum_{k=0}^{\infty}\left[\left(\frac{\eta}{\eta+\mu_x}\right)\left(-\frac{df_k^*(s)}{ds}\Big|_{s=\eta}\right) + \frac{\eta f_k^*(\eta)}{(\eta+\mu_x)^2}\right] \\ &\quad = \frac{\eta(\eta+\mu_y)(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad\quad - \frac{\eta}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y}. \end{aligned} \tag{21}$$

From (20) and (21), (19) is rewritten as

$$\begin{aligned} E[t_{cn}] &= \frac{(1-\alpha)\mu_x(\eta+\mu_x)(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad - \frac{(1-\alpha)\mu_x}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} \\ &\quad + \frac{\eta(\eta+\mu_y)(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad - \frac{\eta}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y}. \end{aligned} \tag{22}$$

Suppose that a call successfully hands over i times. Let $t_{c,i}$ be the period between when the MS moves into cell i and when the call is complete [see Fig. 1(a)]. The period $t_{c,i}$ is called the excess life of t_c, which has the density function $f_{c,i}(t_{c,i})$ for all $i \geq 1$. Let x_j^* denote the period between when the call is handed off to cell i and when x_j ends [see Fig. 1(a)]. If $t_{m,i}$ is exponentially distributed, then from the excess life theorem, x_j^* and x_j have the same density function, and $f_{c,i}(t_{c,i}) = f_c(t_c)$. Let t_{ch} denote the channel occupation time of a handoff call. It is apparent that

$$E[t_{ch}] = E[t_{cn}]. \tag{23}$$

Let t_{cin} denote the channel occupation time of a new call which is either forced to terminate due to an interruption at cell 0 or is handed off to the next cell during the interruption period. The expected value $E[t_{cin}]$ is derived from Appendix B, which is expressed as

$$\begin{aligned} E[t_{cin}] &= \frac{\alpha(1-\beta)\mu_x\mu_y(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad - \frac{1}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} \\ &\quad + \frac{\eta\alpha\mu_x(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad - \frac{\alpha\eta\mu_x}{\mu_y[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]}. \end{aligned} \tag{24}$$

Let t_{cih} denote the channel occupation time of a handoff call which is disconnected due to the interruption. Similar to (23)

$$E[t_{cih}] = E[t_{cin}]. \tag{25}$$

The net traffic ρ to a cell consists of four parts: i) the traffic of $\lambda_o(1-P_{i,1})E[t_{cn}]$ generated by nonforced-terminated new calls, ii) the traffic of $\lambda_o P_{i,1}E[t_{cin}]$ generated by forced-terminated new calls, iii) the traffic of $\lambda_h(1-P_{i,2})E[t_{ch}]$ generated by nonforced-terminated handoff calls, and iv) the traffic of $\lambda_h P_{i,2}E[t_{cih}]$ generated by forced-terminated handoff calls and

$$\begin{aligned} \rho &= \lambda_o(1-P_{i,1})E[t_{cn}] + \lambda_h(1-P_{i,2})E[t_{ch}] \\ &\quad + \lambda_o P_{i,1}E[t_{cin}] + \lambda_h P_{i,2}E[t_{cih}]. \end{aligned} \tag{26}$$

With net traffic ρ, the channel allocation for RES1 can be modeled by an $M/G/C/C$ queue [6], and the blocking probability P_b is expressed as

$$P_b = \frac{(\rho^c/c!)}{\sum_{i=0}^{c}(\rho^i/i!)} \tag{27}$$

where c is the number of channels in a cell. The probability P_b can be obtained by assigning an initial value for λ_h, and then iterating (1) and (27) until the λ_h value converges. Finally, the call incompletion probability can be obtained from (18).

B. An Analytic Model for RES3

The analytic model for RES3 is similar to that for RES1 except for Case III. In this case, MS makes a call reestablishment request to cell 1. If cell 1 has an idle channel, then the call can be reestablished in RES3. We have

$$\begin{aligned}\Pr[\text{Case III in RES3 occurs}] &= \Pr[t_{D,k} < \tau_m < t_{D,k} + y_{k+1} \quad \text{and } y_{k+1} \le z_{k+1}] \\ &= \Pr[\text{Case III or V in RES1 occur}] \times \beta. \end{aligned} \tag{28}$$

From (14), (28) is rewritten as

$$\Pr[\text{CASE III in RES3 occurs}] = \frac{\alpha\beta\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y}. \tag{29}$$

From (8) and (29), $P_{h,1}$ in RES3 is expressed as

$$\begin{aligned} P_{h,1} &= \Pr[\text{Case I in RES3 occurs}] + \Pr[\text{Case III in RES3 occurs}] \\ &= \frac{\eta(\eta+\mu_y)}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y} + \frac{\alpha\beta\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y}. \end{aligned} \tag{30}$$

Since the call is forced to terminate for Cases IV and V in RES3, $P_{i,1}$ is expressed as follows:

$$P_{i,1} = \Pr[\text{Case IV in RES3 occurs}] + \Pr[\text{Case V in RES3 occurs}]. \tag{31}$$

From (14)

$$\begin{aligned}\Pr[\text{Case V in RES3 occurs}] &= \Pr[t_{D,k} < \tau_m < t_{D,k} + y_{k+1} \quad \text{and } y_{k+1} > z_{k+1}] \\ &= (1-\beta) \times \frac{\alpha\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y}. \end{aligned} \tag{32}$$

From (11) and (32), (31) is rewritten as

$$P_{i,1} = \frac{\alpha\mu_x(1-\beta)\mu_y}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y} + \frac{\alpha(1-\beta)\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y}. \tag{33}$$

Similarly

$$P_{h,2} = \frac{\eta(\eta+\mu_y)}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y} + \frac{\alpha\beta\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y} \tag{34}$$

and

$$P_{i,2} = \frac{\alpha\mu_x(1-\beta)\mu_y}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y} + \frac{\alpha(1-\beta)\mu_x\eta}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y}. \tag{35}$$

Following the same derivation for (18), we obtain

$$P_{nc} = P_b + \frac{\lambda_h}{\lambda_o} P_b + (1-P_b)P_{i,1} + \frac{\lambda_h}{\lambda_o}(1-P_b)P_{i,2}. \tag{36}$$

The expected value $E[t_{cn}]$ for RES3 is derived as follows:

$$\begin{aligned} E[t_{cn}] = {} & E[t_c, \text{where } \tau_m > t_c] \\ & + E[\tau_m, \text{where for all } k, t_k < \tau_m < t_k + x_{k+1}] \\ & + E[t_{D,k} + y_{k+1}, \text{where for all } k, \\ & \quad t_{D,k} < \tau_m < t_{D,k} + y_{k+1} \text{ and } y_{k+1} \le z_{k+1}]. \end{aligned} \tag{37}$$

Since $\beta = \Pr[y_{k+1} \le z_{k+1}]$, we have

$$\begin{aligned} & E[t_{D,k} + y_{k+1} \text{ where for all } k, t_{D,k} < \tau_m < t_{D,k} + y_{k+1} \\ & \quad \text{and } y_{k+1} \le z_{k+1}] \\ & = E[t_{D,k} + y_{k+1} \text{ where for all } k, \\ & \quad t_{D,k} < \tau_m < t_{D,k} + y_{k+1}]\,\beta. \end{aligned} \tag{38}$$

From (48) and (52), we have

$$\begin{aligned} & E[t_{D,k} + y_{k+1} \text{ where for all } k, \\ & \quad t_{D,k} < \tau_m < t_{D,k} + y_{k+1} \text{ and } y_{k+1} \le z_{k+1}] \\ & = \frac{\eta\alpha\beta\mu_x(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y]^2} - \frac{\alpha\beta\eta\mu_x}{\mu_y[(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y]}. \end{aligned} \tag{39}$$

From (20), (21), and (39), we have

$$\begin{aligned} E[t_{cn}] = {} & \frac{(1-\alpha)\mu_x(\eta+\mu_x)(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y]^2} - \frac{(1-\alpha)\mu_x}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y} \\ & + \frac{\eta(\eta+\mu_y)(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y]^2} - \frac{\eta}{(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y} \\ & + \frac{\eta\alpha\beta\mu_x(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y]^2} - \frac{\alpha\beta\eta\mu_x}{\mu_y[(\eta+\mu_x)(\eta+\mu_y) - \alpha\beta\mu_x\mu_y]}. \end{aligned} \tag{40}$$

Similar to the derivation for (23), $E[t_{ch}] = E[t_{cn}]$. $E[t_{cin}]$ is derived as follows:

$$\begin{aligned} E[t_{cin}] = {} & E[t_{c'} \text{ where } t_{c'} < \tau_m] \\ & + E[t_{D,k} + y_{k+1}, \text{where for all } k, \\ & \quad t_{D,k} < \tau_m < t_{D,k} + y_{k+1} \text{ and } y_{k+1} > z_{k+1} \end{aligned} \tag{41}$$

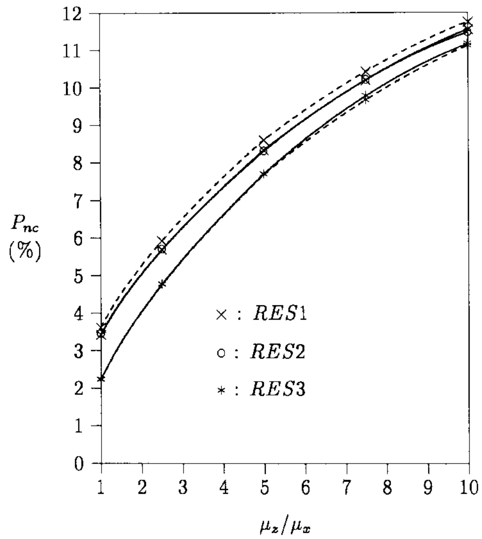


Fig. 7. The effect of μ_z (solid: simulation; dashed: analysis).

where

$$\begin{aligned} &E[t_{D,k} + y_{k+1}, \text{where for all } k, \\ &\quad t_{D,k} < \tau_m < t_{D,k} + y_{k+1} \text{ and } y_{k+1} > z_{k+1}] \\ &\quad = E[t_{D,k} + y_{k+1} \text{ where for all } k, \\ &\qquad t_{D,k} < \tau_m < t_{D,k} + y_{k+1}] \times (1-\beta). \end{aligned} \tag{42}$$

From (47), (48), and (52), (41) is rewritten as

$$\begin{aligned} E[t_{cin}] = &\frac{\alpha(1-\beta)\mu_x\mu_y(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &- \frac{1}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} \\ &+ \frac{\eta\alpha(1-\beta)\mu_x(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &- \frac{\alpha(1-\beta)\eta\mu_x}{\mu_y[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]}. \end{aligned} \tag{43}$$

Similar to (23)

$$E[t_{cih}] = E[t_{cin}]. \tag{44}$$

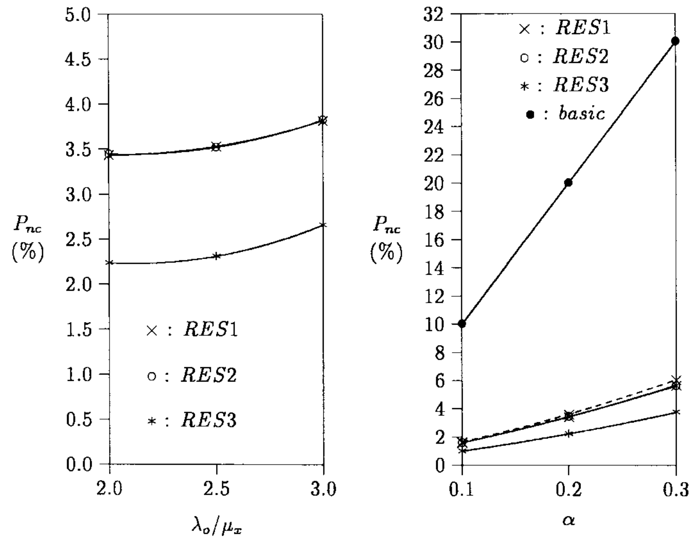
Following the same reasoning for (28), the net traffic ρ for RES2 is

$$\begin{aligned} \rho = &\lambda_o(1-P_{i,1})E[t_{cn}] + \lambda_h(1-P_{i,2})E[t_{ch}] \\ &+ \lambda_o P_{i,1}E[t_{cin}] + \lambda_h P_{i,2}E[t_{cin}]. \end{aligned} \tag{45}$$

The probability P_b for RES3 can be obtained by the same interactive algorithm for RES1, and the call incompletion probability can obtained from (36).

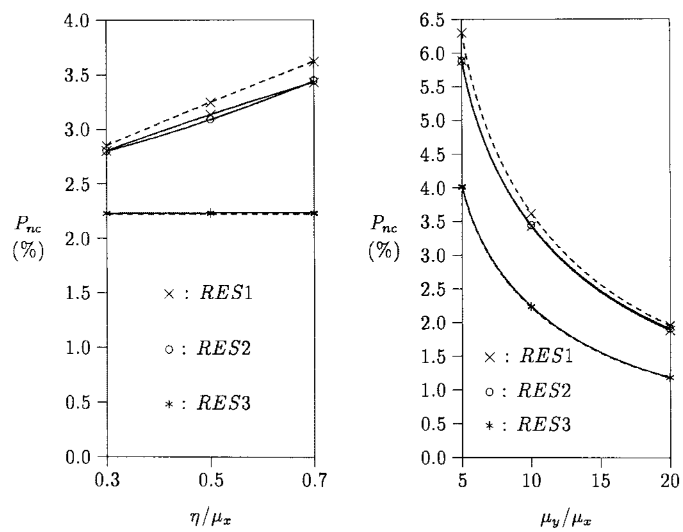
C. Simulation Validation

The analytic models were validated by simulation experiments. In the simulation experiments, we considered 6 × 6 wrapped mesh cell structure. The simulation model follows the discrete event approach as in [7] and [5]. RES2 is evaluated by simulation experiments without analytic modeling. In Figs. 7–9, the solid curves represent the P_{nc} curves based on simulation, and the dashed curves are based on analysis.



(a) (b)

Fig. 8. The effects of λ_o and α (solid: simulation; dashed: analysis). (a) The effect of λ_o and (b) the effect of α.



(a) (b)

Fig. 9. The effects of η and μ_y (solid: simulation; dashed: analysis). (a) The effect of η and (b) the effect of μ_y.

These figures indicate that both analysis and simulation are consistent.

IV. Performance Evaluation

This section compares the performance (specifically P_{nc}) of the three call reestablishment algorithms. In this comparison, input parameters such as η, λ_o, and μ_y are normalized by μ_x. For example, if the expected time of a conversation period $(1/\mu_x) = 30$ s, then $\mu_y = 10\mu_x$ means that the expected interruption time is 3 s.

Effect of μ_z: Fig. 7 plots P_{nc} as a function of μ_z, where $\alpha = 0.2$, $\eta = 0.7\mu_x$, $\lambda_o = 2\mu_x$, and $\mu_y = 10\mu_x$. Note that P_{nc} for the basic scheme (GSM without call reestablishment) is about 20% for all μ_z values, which is not shown in Fig. 7. The figure indicates that P_{nc} increases as μ_z increases for all three RES algorithms (because the larger the μ_z, the higher the probability that $y_i > z_i$, and thus the probability of call dropping). We observe that the P_{nc} for both RES1 and RES2 are almost identical. When $\mu_z = \mu_x$, RES3 results in 35% improvement over RES1 and RES2. When $\mu_z = 10\mu_x$, the improvement of RES3 becomes insignificant. For a large μ_z, an interrupted call is likely to be forced to terminate due to z_i expiration, no matter the MS moves into a new cell or not. In this case, three call reestablishment algorithms have the similar performance. Thus, we conclude that RES3 significantly outperforms RES1 and RES2 when μ_z is small.

Effect of λ_o*:* Fig. 8(a) plots P_{nc} as a function of λ_o, where $\alpha = 0.2$, $\eta = 0.7\mu_x$, $\mu_y = 10\mu_x$, and $\mu_z = 1.0\mu_x$. It is apparent that P_{nc} increases as λ_o increases. The figure indicates that RES1 and RES2 have the same performance. When $\lambda_o = 2.0\mu_x$, RES3 has 35% improvement over RES1 and RES2. When $\lambda_o = 3.0\mu_x$, the improvement is 30.3%. Thus, the improvement of RES3 over RES1 and RES2 becomes more significant as λ_o decreases.

Effect of α*:* Fig. 8(b) plots P_{nc} against α, where $\eta = 0.7\mu_x$, $\lambda_o = 2\mu_x$, $\mu_y = 10\mu_x$, and $\mu_z = 1.0\mu_x$. As α increases, a call is more likely to be interrupted, and P_{nc} is larger. When $\alpha = 0.1$, RES1 and RES2 outperform the GSM basic scheme by 84%. When $\alpha = 0.3$, the improvement is 81%. Thus, RES1 and RES2 significantly outperform the basic scheme for all α values. When $\alpha = 0.1$, RES3 outperforms RES1 and RES2 by 37.2%. When $\alpha = 0.3$, RES3 outperforms RES1 and RES2 by 33.8%.

Effect of η*:* Fig. 9(a) illustrates the P_{nc} performance for various mobility rate η, where $\alpha = 0.2$, $\lambda_o = 2\mu_x$, $\mu_y = 10\mu_x$, and $\mu_z = 1.0\mu_x$. Fig. 9(a) shows that P_{nc} increases as η increases for RES1 and RES2. For a large η, an MS is likely to move to a new cell during an interruption period. For RES3, P_{nc} is not effected by η because the interrupted calls can be reestablished when the MS moves to a new cell. With $\eta = 0.3\mu_x$, RES3 outperforms RES1 and RES2 by 20%, and with $\eta = 0.7\mu_x$, RES3 outperforms RES1 and RES2 by 35%. Thus, the improvement of RES3 over RES1 and RES2 becomes significant as η increases.

Effect of μ_y*:* Fig. 9(b) plots P_{nc} as a function of μ_y, where $\alpha = 0.2$, $\eta = 0.7\mu_x$, $\lambda_o = 2\mu_x$, and $\mu_z = 1\mu_x$. This figure indicates that P_{nc} decreases as μ_y increases. Note that increasing μ_y has the same effect as decreasing μ_z. When $\mu_y = 5\mu_x$, RES3 outperforms RES1 and RES2 by 31.8%. When $\mu_y = 20\mu_x$, RES3 outperforms RES1 and RES2 by 37.2%. Thus, the improvement of RES3 over RES1 and RES2 becomes significant as μ_y increases.

V. Conclusion

We proposed analytic models to investigate the performance for GSM call reestablishment service. The call reestablishment algorithms under evaluation are RES1 (the radio channel is reserved during interruption; the call is not reestablished if the MS moves into a new cell), RES2 (the radio channel is not reserved during interruption; the call is not reestablished if the MS moves into a new cell), and RES3 (the radio channel is reserved during interruption; the call is reestablished if the MS moves into a new cell). The analytic models are validated by simulation experiments. Our study indicated that call reestablishment can significantly reduce the call incompletion probability for interrupted calls (more than 80% improvement was observed in most cases of this paper). Furthermore, we observed that both RES1 and RES2 have the same performance, and RES3 may significantly outperform RES1 and RES2, especially for long z_i, small call arrival rate λ_o and large mobility rate η.

Appendix A
Input Parameters and Output Measures

The input parameters and output measures used in this paper are listed as follows.

Input Parameters

λ_o	New call arrival rate to a cell.
x_i	ith conversation period.
$1/\mu_x$	Mean conversation period time.
y_i	ith interruption period.
$1/\mu_y$	Mean interruption period time.
α	Probability that at the end of a conversation period, the radio channel is interrupted.
z_i	ith interval between when the interruption begins and when the first of the following two events occurs: i) the interruption timer expires and ii) the remote party hangs up the phone.
$t_{m,i}$	Residence time of the MS at cell i.
$1/\eta$	Mean MS residence time.
τ_m	Period between the arrival of the call and when the MS moves out of cell 0.

Output Measures

λ_h	Handoff call arrival rate to the cell.
P_b	Probability that all channels are busy when a call (either a new call or a handoff call) arrives.
$P_{h,1}$ ($P_{h,2}$)	Probability that a connected new (handoff) call at the cell will handoff to the next cell.
$P_{i,1}$ ($P_{i,2}$)	Probability that a connected new (handoff) call at the cell will be disconnected due to interruption.
P_{nc}	Probability that a call is not completed.
β	Probability that a call is reestablished after interruption.
t_c	Call holding time of a complete call without considering the handoff effect.
t_k	Holding time for the first k cycles of a call.
t_{cn}	Channel occupation time of a new call that is either complete in a cell or handed off to the next cell.
t_{ch}	Channel occupation time of a handoff call.
t_{cin}	Channel occupation time of a new call which is either forced to terminate due to an interruption at cell 0 or is handed off to the next cell during the interruption period.

t_{cih}	Channel occupation time of a handoff call which is disconnected due to the interruption.
$t_{c,i}$	Period between when the MS moves into cell i and when the call is complete.
ρ	Net traffic to a cell.

Appendix B
Derivation of $E[t_{cin}]$

This appendix derives the expected value $E[t_{cin}]$ as follows:

$$\begin{aligned}E[t_{cin}] &= E[t_{c'} \text{ where } t_{c'}<\tau_m] \\ &\quad + E[t_{D,k}+y_{k+1} \text{ where for all } k, \\ &\qquad t_{D,k}<\tau_m<t_{D,k}+y_{k+1}] \\ &= E[t_{c'} \text{ where } t_{c'}<\tau_m] \\ &\quad + E[t_{D,k} \text{where for all } k, t_{D,k}<\tau_m<t_{D,k}+y_{k+1}] \\ &\quad + E[y_{k+1} \text{ where for all } k, \\ &\qquad t_{D,k}<\tau_m<t_{D,k}+y_{k+1}]. \end{aligned} \tag{46}$$

Following the same derivation for (20), we have

$$\begin{aligned}E[t_{c'} \text{where } t_{c'}<\tau_m] &= -\left.\frac{df^*_{c'}(s)}{ds}\right|_{s=\eta} \\ &= \frac{\alpha(1-\beta)\mu_x\mu_y(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad - \frac{1}{(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y} \end{aligned} \tag{47}$$

and

$$\begin{aligned}&E[t_{D,k} \text{ where for all } k, t_{D,k}<\tau_m<t_{D,k}+y_{k+1}] \\ &= \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty}\int_{\tau_m=t_{D,k}}^{\infty}\int_{y_{k+1}=\tau_m-t_{D,k}}^{\infty} t_{D,k}f_{D,k}(t_{D,k}) \right. \\ &\qquad \left. \times\ \eta e^{-\eta\tau_m}\mu_y e^{-\mu_y y_{k+1}}dy_{k+1}d\tau_m dt_{D,k}\right] \\ &= \left(\frac{\eta}{\eta+\mu_y}\right) \\ &\quad \times\left\{\sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty} t_{D,k}f_{D,k}(t_{D,k})e^{-\eta t_{D,k}}dt_{D,k}\right]\right\} \\ &= \left(\frac{\eta}{\eta+\mu_y}\right)\left\{\sum_{k=0}^{\infty}\left[-\left.\frac{f^*_{D,k}(s)}{ds}\right|_{s=\eta}\right]\right\} \\ &= \frac{\eta\alpha\mu_x(2\eta+\mu_x+\mu_y)}{[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]^2} \\ &\quad - \frac{\eta\alpha\mu_x}{(\eta+\mu_y)[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]}. \end{aligned} \tag{48}$$

Since

$$\begin{aligned}&\int_{y_{k+1}=\tau_m-t_{D,k}}^{\infty} y_{k+1}\mu_y e^{-\mu_y y_{k+1}}\ dy_{k+1} \\ &\quad = (\tau_m-t_{D,k})e^{-\mu_y(\tau_m-t_{D,k})} - \frac{1}{\mu_y}e^{-\mu_y(\tau_m-t_{D,k})}\end{aligned}$$

we have

$$\begin{aligned}&E[y_{k+1} \text{ where for all } ;k, t_{D,k}<\tau_m<t_{D,k}+y_{k+1}] \\ &= \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty}\int_{\tau_m=t_{D,k}}^{\infty} f_{D,k}(t_{D,k})\eta e^{-\eta\tau_m}(\tau_m-t_{D,k})\right. \\ &\qquad \left.\times\ e^{-\mu_y(\tau_m-t_{D,k})}d\tau_m dt_{D,k}\right] \\ &\quad - \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty}\int_{\tau_m=t_{D,k}}^{\infty} f_{D,k}(t_{D,k})\eta e^{-\eta\tau_m}\right. \\ &\qquad \left.\times\ \frac{1}{\mu_y}e^{-\mu_y(\tau_m-t_{D,k})}\ d\tau_m\ dt_{D,k}\right] \\ &= D - E \end{aligned} \tag{49}$$

here

$$\begin{aligned}D &= \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty}\int_{\tau_m=t_{D,k}}^{\infty} f_{D,k}(t_{D,k})\eta e^{-\eta\tau_m}\right. \\ &\qquad \left.\times\ (\tau_m-t_{D,k})e^{-\mu_y(\tau_m-t_{D,k})}\ d\tau_m dt_{D,k}\right] \\ &= \sum_{k=0}^{\infty}\left\{\int_{t_{D,k}=0}^{\infty} f_{D,k}(t_{D,k})\left[\frac{\eta}{(\eta+\mu_y)^2}\right]\right. \\ &\qquad \left.\times\ e^{-(\eta+\mu_y)t_{D,k}}\ dt_{D,k}\right\} \\ &= \left[\frac{\eta}{(\eta+\mu_y)^2}\right]\left[\sum_{k=0}^{\infty} f^*_{D,k}(\eta)\right] \\ &= \frac{\eta\alpha\mu_x}{(\eta+\mu_y)[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]} \end{aligned} \tag{50}$$

and

$$\begin{aligned}E &= \sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty}\int_{\tau_m=t_{D,k}}^{\infty} f_{D,k}(t_{D,k})\eta e^{-\eta\tau_m}\right. \\ &\qquad \left.\times\left(\frac{1}{\mu_y}\right)e^{-\mu_y(\tau_m-t_{D,k})}\ d\tau_m\ dt_{D,k}\right] \\ &= \left[\frac{\eta}{\mu_y(\eta+\mu_y)}\right] \\ &\quad \times\left\{\sum_{k=0}^{\infty}\left[\int_{t_{D,k}=0}^{\infty} f_{D,k}(t_{D,k})e^{-\eta t_{D,k}}\ dt_{D,k}\right]\right\} \\ &= \left[\frac{\eta}{\mu_y(\eta+\mu_y)}\right]\left[\sum_{k=0}^{\infty} f^*_{D,k}(\eta)\right] \\ &= \frac{\alpha\eta\mu_x}{\mu_y[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]}. \end{aligned} \tag{51}$$

From (50) and (51), (49) is rewritten as

$$\begin{aligned}&E[y_{k+1} \text{ where for all } k, t_{D,k}<\tau_m<t_{D,k}+y_{k+1}] \\ &\quad = \frac{\eta\alpha\mu_x}{(\eta+\mu_y)[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]} \\ &\qquad - \frac{\alpha\eta\mu_x}{\mu_y[(\eta+\mu_x)(\eta+\mu_y)-\alpha\beta\mu_x\mu_y]}. \end{aligned} \tag{52}$$

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