A Handset-Based Solution for Reducing International Roaming Costs

Yi-Bing Lin, *Fellow, IEEE,* Ren-Huang Liou, Yuan-Kai Chen, and Chai-Hien Gan, *Member, IEEE*

***Abstract*—Today's mobile service providers allow their users to receive telecom services when they roam to other countries. However, international roaming is very expensive. In the standard mobile call setup procedure, a call from the visited country to a roaming user in that country results in two international calls. This phenomenon is referred to as the tromboning effect. Several third-party solutions have been proposed to resolve the tromboning problem by replacing two international calls with two local calls. These solutions require one or more gateways for call re-routing. This paper proposes a handset-based solution that does not need to add/modify network nodes in the existing mobile telecom systems. Analytic modeling and simulation experiments indicate that our solution is effective in international trunk elimination and call setup signaling.**

***Index Terms*—Callback, international roaming, mobile telecom service, tromboning.**

I. Introduction

EXISTING mobile service providers allow their users to receive telecom services when they roam to other countries. However, international roaming is very expensive according to *3rd Generation Partnership Project* (3GPP) [1], [2]. In the standard mobile call setup procedure (referred to as the 3GPP procedure), a call from the visited country to a roaming user in that country results in two international calls (while people expect it to be a local call). To explain why these international trunks are involved, let us first give some definitions and facts.

Definition 1. A user who subscribes to mobile telecom services in country A is assigned an E.164 mobile telephone number called *Mobile Station ISDN number* (MSISDN), and country A is called the home country of the user. Every MSISDN is mapped to a *Gateway Mobile Switching Center* (GMSC) located in the home network of the user (in country A).

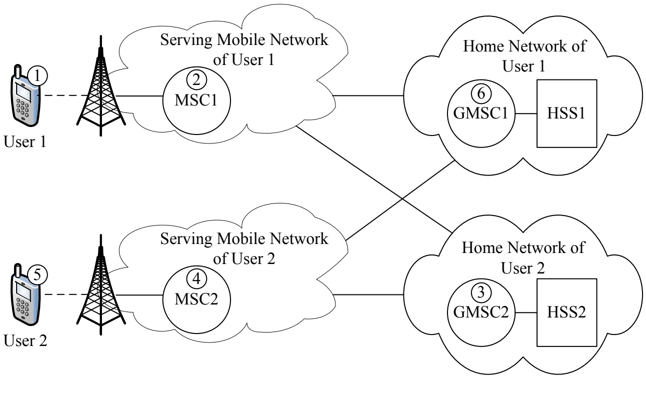

Fig. 1. Network architecture for mobile-to-mobile call.

To receive telecom services, every mobile user is connected to a serving *Mobile Switching Center* (MSC), and this user is associated with a GMSC as described in Definition 1. In Figure 1, user 1 associated with GMSC1 is served by MSC1, and user 2 associated with GMSC2 is served by MSC2.

Definition 2. A mobile-to-mobile call setup defined by 3GPP consists of three segments (when the caller is a fixed network user, the call setup is similar and the description is omitted) [1], [2]:

- **(a) Originating Segment:** When user 1 (Figure 1 (1)) dials user 2's MSISDN (Figure 1 (5)), the call is first routed from user 1's serving MSC (Figure 1 (2)) to user 2's GMSC (Figure 1 (3)).
- **(b) Querying Segment:** GMSC2 queries user 2's *Home Subscriber Server* (HSS) to identify the serving MSC of user 2 (Figure 1 (4)). The HSS returns the *Mobile Station Roaming Number* (MSRN; the SS7 number of MSC2).
- **(c) Terminating Segment:** Based on the MSRN (which points to the location of MSC2), GMSC2 routes the call to user 2 (Figure 1 (5)) through MSC2.

Directly from the terminating and the originating segments described in Definition 2, we have the following two facts:

Fact 1 (Mobile Call Termination). When someone calls a user by dialing his/her MSISDN, this incoming call is always routed to the GMSC of the user.

Fact 2 (Mobile Call Origination). For an outgoing call dialed by a user, the call setup does not involve the user's GMSC.

With the above background understanding of the standard

Manuscript received June 25, 2010; revised December 15, 2010; accepted February 23, 2011. The associate editor coordinating the review of this paper and approving it for publication was B. Liang.

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Y.-B. Lin's work was supported in part by NSC 98-2219-E-009-016, 98-2221-E-009-059-MY2, 97-2221-E-009-143-MY3, Chunghwa Telecom, IBM, ITRI and the NCTU Joint Research Center, and the MoE ATU plan.

C.-H. Gan's work was sponsored in part by the Information and Communications Research Laboratories (ICL), Industrial Technology Research Institute (ITRI), Taiwan, Republic of China (ITRI Grant Project Code A352BW2100 and A301AR2F00).

Digital Object Identifier 10.1109/TWC.2011.032411.101124

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3GPP mobile call setup procedure described in Definition 1, we proceed to describe the international roaming issue. A user of country A who travels to country B is called a *roamer*. The serving network and the home network of a roamer are located in different countries.

Fact 3. Suppose that a user of country A roams to country B. If someone calls this roamer from a country other than A, then two international trunks are required in the call path following the 3GPP procedure.

In Figure 1, if home network of user 2 is located in country A, serving network of user 2 is in country B, and serving network of user 1 is in country C, then according to Definition 2, call setup from user 1 to user 2 involves two international trunks (2)-(3) (from country C to country A) and (3)-(4) (from A to B). This call setup is *triangular*. If B and C are the same country, then the call setup is *tromboning* (i.e., (2)-(3) and (3)-(4) are international trunks between A and B). To optimize the call path between user 1 and user 2, the voice trunks should be set up directly from serving network of user 1 to serving network of user 2 without involving the GMSC at home network of user 2 (i.e., two international trunks are eliminated in the tromboning case, and one international trunk is eliminated in the triangular case). Skype and other VoIP solutions [3]-[6] resolve tromboning/triangular issue for Internet users. However, they do not work for E.164 telephone numbers in Definition 1 because a GMSC is controlled by the telecom network, and is always connected in the voice call path (Fact 1).

To eliminate tromboning/triangular problem, call setup to a roamer should avoid involvement of the roamer's GMSC. 3GPP TS 22.079 proposes a solution for tromboning elimination [7]. This approach requires modifications to the dialing method (i.e., the caller should know exactly that callee is roaming and then dial extra digits besides callee's MSISDN), which is not convenient to the users and is therefore seldom used by the mobile telecom operators. Several solutions have been proposed with standard number dialing. These solutions utilize plug-in gateways to conduct routing without involving the roamer's GMSC [8]-[10]. In these solutions, a caller dials a roamer's phone number following the standard dialing method, and therefore is acceptable to the users.

While the above network-based solutions efficiently resolve the tromboning issues, they require installation of extra gateways in the telecom networks. This paper considers a handset-based solution that does not require modifications to the telecom network. We first describe the algorithm for eliminating tromboning/triangular problem for a roamer. Then we investigate the performance of the algorithm.

II. ELIMINATING TROMBONING/TRIANGULAR PROBLEM THROUGH CALLBACK

Our solution utilizes *CallBack Mechanism* (CBM) described below.

Definition 3 (CallBack Mechanism). Suppose that user 1 calls user 2. With CBM, user 2 first rejects the call and then makes a new call back to user 1.

Due to Fact 2, CBM can eliminate tromboning/triangular routing when user 2 calls back to user 1. Note that the callback mechanism has been used to provide cheap international call services by routing an international call through a third country [11], [12]. Such solutions do not attempt to resolve the tromboning/triangular issue for mobile users. On the other hand, our callback mechanism intents to resolve this issue.

For the discussion purpose, we summarize four situations where the caller (user 1) makes a call to a roamer (user 2):

Situation 1. User 1 and user 2 come from the same home country, and user 1 is not roaming.

Situation 2. User 1 and user 2 come from the same home country, and user 1 is roaming.

Situation 3. User 1 and user 2 come from different home countries, and user 1 is not roaming.

Situation 4. User 1 and user 2 come from different home countries, and user 1 is roaming.

Fact 4. Suppose that user 2 roams from country A to country B. User 1 is a user of country B and is not roaming (Situation 3). When user 1 calls user 2, CBM eliminates tromboning/triangular routing.

In Fact 4, the 3GPP procedure results in path (1)-(2)-(3)-(4)-(5) in Figure 1, where (2)-(3) and (3)-(4) are tromboning international trunks. If user 2 rejects this call and makes another call to user 1, then according to Definition 2, the call path is (5)-(4)-(6)-(2)-(1). The home network of user 1, the serving network of user 1, and the serving network of user 2 all locate in country B. Since the GMSC of user 2 is not involved (Fact 2), the call does not involve international trunk, and the tromboning routing is avoided.

Fact 5. Suppose that user 2 roams from country A to country B. User 1 is a user of country A and is not roaming (Situation 1). When user 1 calls user 2, CBM replaces the international trunk from GMSC2 to user 2 by another international trunk from GMSC1 to user 1.

Following Definition 2, Fact 5 indicates that CBM does not reduce the international trunk cost if the caller and the roamer have the same home network.

Fact 6. Suppose that user 2 roams from country A to country B, and user 1 roams from C to B (Situations 2 and 4 where C is or is not A). If user 1 calls user 2, then CBM does not reduce the international trunk cost.

In Fact 6, after the call from user 1 to user 2 is rejected, the callback path from user 2 to user 1 is (5)-(4)-(6)-(2)-(1) in Figure 1, which still includes two international trunks (4)-(6) and (6)-(2); i.e., GMSC2 is replaced by GMSC1. In Situations 1, 2, and 4, the voice trunk cost for CBM is the same as that for the 3GPP procedure. From Facts 4 and 6, we have the following theorem:

Theorem 1. Suppose that user 2 roams from country A to country B, and user 1 calls user 2. If user 2 exercises CBM, tromboning/triangular routing is eliminated if and only if user 1 is not roaming.

From Definition 3 and Fact 6, we have a follow-up fact:

Fact 7. If both call parties are roamers and both exercise CBM in a call setup (Situations 2 and 4), then they will continue calling back each other in an infinite loop.

It is clear that in Situation 1, the 3GPP procedure is already optimal, and exercising CBM results in same voice trunk setup as the 3GPP procedure (Fact 5). For Situation 3, CBM can effectively eliminate tromboning/triangular routing (Fact 4). Note that Theorem 1 covers both Situations 1 and 3; that is, although CBM does not reduce international trunk cost in Situation 1, no tromboning/triangular routing will occur if CBM is executed. Our experience from mobile telecom operators indicates that excluding the incoming calls from the home country (Situation 1), over 95% of the calls to a roamer come from Situation 3. Therefore, CBM is an effective solution for reducing international roaming costs, which does not need to modify any network component. However, CBM may cause infinite callback looping in Situations 2 and 4 (as described in Fact 7). We further note that most mobile networks do not show (i.e., withhold) roamers' MSISDNs when they make calls, and the looping problem will not occur (because the callees can not call back). To take the advantage of CBM without incurring the looping problem (if the roaming caller's MSISDN is not withheld), we design an algorithm called *Roamer's CallBack* (RCB) installed in a handset.

III. ROAMER'S CALLBACK ALGORITHM

This section proposes a modified version of CBM called *Roamer's CallBack* algorithm (RCB). When someone calls a roamer, RCB of the roamer's handset will automatically call back after the roamer accepts the call, and the roamer handles the call just like a normal call setup (in other words, he/she does not know that a callback occurs). If the caller also installs RCB, when he/she makes a call to the roamer, RCB of the caller will automatically terminate the first call (which was rejected by the callee's RCB), and will accept the subsequent callback. The caller will experience normal call setup without terminating the first call manually and will not notice the callback. This algorithm also avoids the infinite callback looping described in Fact 7. RCB for incoming call (referred to as RCB-I) is described in the following steps (we assume that user 1 calls user 2, and RCB-I is exercised at user 2's handset).

Algorithm RCB-I:

Step 1.1. If (a) the country code of user 1's MSISDN is the same as that of user 2's MSISDN, (b) user 1's MSISDN is withheld, or (c) user 2 is not roaming, then executes the 3GPP call termination procedure (i.e., callback is not triggered). Otherwise (user 2 is roaming, and the home country of user 1 is different from that of user 2), execute Step 1.2.

Step 1.2. (a) Automatically reject the call by sending busy tone to user 1, (b) ring user 2 as a normal incoming call, and (c) set timer $T1$. If user 2 does not pick up the handset by $T1$, then exit (the call is terminated). Otherwise (user 2 accepts the call), execute Step 1.3.

Step 1.3. A callback is set up to user 1 following the 3GPP call origination procedure (see Definition 2 (a)), and a timer $T2$ is set. This callback may fail if the caller has not hung up the handset (to terminate the first call which is rejected by RCB-I at Step 1.2 (a)). In this case, RCB-I will receive busy tone and terminate this callback immediately. Then it repeats calling back until either the call is connected, user 1 rejects the call, or $T2$ expires.

Considering Theorem 1 and Fact 4, Step 1.1 triggers callback if user 2 is roaming and the country code of user 2's MSISDN is different from that of user 1's MSISDN. Note that RCB-I always assumes that user 1 is not roaming if his/her MSISDN is not withheld. As we pointed out before, many telecom operators withhold the caller ID of an outgoing call from a roamer. Therefore, if user 1's MSISDN is not withheld, user 1 typically does not roam. For (c) of Step 1.1, "detecting whether user 2 is roaming" can be done with low cost [9], [10]. In Step 1.2, the busy tone "hints" user 1 that he/she will receive a callback. Busy tone is used in RCB because in common understanding, this tone means that user 2 is not available now, but may want to connect the call later. User 1 will hang up the call when he/she hear the busy tone. If user 1 also installs the RCB software in the handset, then the software will automatically handle this busy-tone case (RCB for outgoing call will be elaborated later). At Step 1.3, there are two possibilities. If user 2 does not picks up the handset within $T2$, the call is actually terminated, and user 1 will not receive a follow-up callback. If user 2 does pick up the handset, a callback will be set up to user 1. If user 1 is hearing the busy tone of the first call without taking any action, then this callback fails because user 1 has not hung up the handset (this case occurs when user 1 does not install the RCB software). Following the 3GPP procedure, MSC1 will also send busy tone back to user 2 (because user 1 is still engaged in the call setup procedure of the first call). User 2's RCB-I will keep calling back to user 1. If user 1 picks up the handset, then the call is connected. If user 1 rejects the call, then this international call setup is terminated. If $T2$ expires, then the call is terminated. Note that timers $T1$ and $T2$ are standard telecom call setup timers that will not be elaborated further.

In the above call setup procedure, the caller will receive a busy tone after he/she dials the callee's MSISDN. After the caller hangs up the call, he/she will receive a callback from the callee. If the caller also installs RCB, then he/she needs not to manually terminate the call and pick up the callback. If the callee is engaged in another call, and is actually busy, RCB still works with a slight modification: after the callee finishes the current call, RCB will remind him/her that there is a missing call, and ask if the callee wants to call back.

Note that automatic callback may create potential attacks (e.g., an attacker calls the RCB user to trigger a callback to an expensive 080 phone number). To avoid the attacks, the home telecom operator typically advises the roamers (e.g., through short messages) to disable some features (such as voice mailbox, 080 pay phone dialing and so on) when they arrive at the visited country. These phone features can be automatically disabled through RCB [13]. Furthermore, at Step 1.2 of RCB-I, the roamer can determine if he/she wants to accept the call based on user 1's MSISDN. Therefore, the roamer personally screens the call before RCB calls back.

Algorithm RCB for outgoing call (referred to as RCB-O) is described in the following steps (we assume that user 1 calls user 2, and RCB-O is exercised at user 1's handset).

Algorithm RCB-O:

Step 2.1. Set up the call to user 2 following the 3GPP call origination procedure (Definition 2).

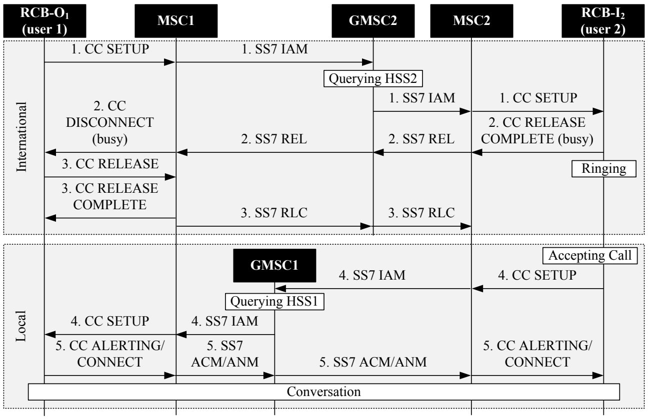

Fig. 2. The RCB call setup message flow.

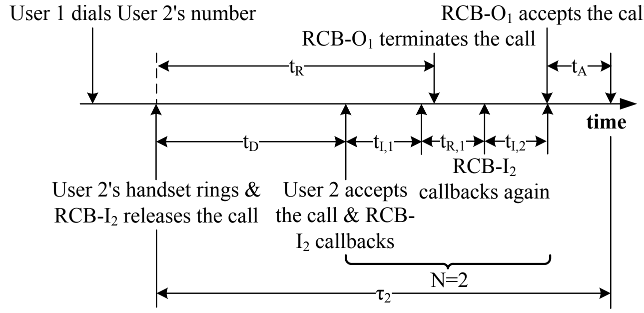

Fig. 3. Timing diagram for the RCB call setup (both users 1 and 2 have installed the RCB software).

- **Step 2.2.** If user 2 accepts the call, then the call is connected and both sides start conversation. If user 2 rejects the call (or does not respond within a timeout period), then RCB-O will receive a reject message, and will terminate the call. Otherwise (user 2 replies a busy tone), execute Step 2.3.
- **Step 2.3.** Terminate the call but do not inform user 1 that the call is terminated. Set a timer $T3$. If user 2 calls back before $T3$ expires, accept the call. Otherwise ($T3$ expires), inform user 1 to exit the call.

Step 2.2 handles the normal call setup case when RCB-I is not exercised at user 2's side. At Step 2.3, if user 1 receives a busy tone, then its RCB-O assumes that user 2 will call back. Timer $T3$ is used to detect if user 2 is actually "busy". If so, RCB-O of user 1 terminates the call when $T3$ expires. To avoid looping, RCB-O never calls back. In other words, for Situations 2 and 4 (which rarely occur), RCB-O will accept the call through the callback originated from the callee, and the voice trunk cost is the same as that of the 3GPP procedure.

In terms of billing, RCB significantly reduces the payments for both calling and called parties in Situation 3. In Figure 1, if the call from user 1 to user 2 is set up by the standard 3GPP procedure, then user 1 pays for the international call (2)-(3), and user 2 pays for another international call (3)-(4). For RCB, either user 2 pays for a local call (4)-(6)-(2) (if calling-party-pay billing is exercised) or both user 1 and user 2 share the cost of the local call (if both-party-pay billing is exercised).

The messages exchanged between RCB-O$_1$, RCB-O of user 1 (caller), and RCB-I$_2$, the RCB-I of user 2 (callee), are described below (see Figure 2).

- **Path 1 (international).** RCB-O$_1$ initiates the call following the 3GPP procedure (Step 2.1). The *Call Control* (CC) SETUP message is sent from user 1's handset to MSC1. Based on user 2's MSISDN, MSC1 routes the call to GMSC2 by sending *Signaling System Number 7* (SS7) Initial Address Message (IAM). After querying HSS2, GMSC2 obtains the MSRN and routes the IAM message to MSC2 as described in Definition 2 (b). MSC2 sends the SETUP message to user 2's handset. This international path involves both visited and home countries.
- **Path 2 (international).** Upon receipt of the SETUP message, RCB-I$_2$ detects that the country code of user 1's MSISDN is different from that of user 2's MSISDN (Step 1.1). Since user 2 is roaming, RCB-I$_2$ rejects the call by sending the CC RELEASE COMPLETE message with the cause "user busy" to MSC2 (Step 1.2 (a)). MSC2 sends the SS7 Release (REL) message to MSC1 through GMSC2, and MSC1 sends the CC DISCONNECT message with the cause "user busy" to user 1. RCB-O$_1$ detects that user 2 is busy and expects to receive a callback from user 2 (Step 2.2).
- **Path 3 (international).** RCB-O$_1$ sends the CC RELEASE message to terminate the call. Then MSC1 replies the RELEASE COMPLETE message to RCB-O$_1$. MSC1 also releases the SS7 trunk by sending the SS7 Release Complete (RLC) message to MSC2.
- **Path 4 (local).** When RCB-I$_2$ rejects the call (see Path 2), it rings user 2 (Step 1.2 (b)). If user 2 picks up the handset, then RCB-I$_2$ automatically performs callback by sending the SETUP message to MSC2 (Step 1.3). MSC2 sends the IAM message to MSC1 locally through GMSC1 without involving GMSC2.
- **Path 5 (local).** RCB-O$_1$ accepts the call by automatically sending CC ALERTING and then CC CONNECT to MSC1 (Step 2.3). MSC1 sends the SS7 Address Complete Message (ACM) and then the SS7 Answer Message (ANM) to MSC2. MSC2 sends the ALERTING and the CONNECT messages to user 2. RCB-I$_2$ connects the call, and conversation starts.

IV. ANALYTIC MODELING

This section investigates the call setup delays for RCB and the 3GPP procedure. Figure 3 illustrates the timing diagram for RCB (i.e., both users 1 and 2 install the RCB software). In Figure 3, RCB-O$_1$ and RCB-I$_2$ represent user 1's RCB-O and user 2's RCB-I, respectively. We assume that the REL/RELEASE COMPLETE delay t_R of the international path (5)→(4)→(3)→(2)→(1) in Figure 1 (Path 2 in Figure 2) is a random variable with the density function $f_R(\cdot)$, the mean $1/\lambda_R$, the variance V_R, and the Laplace transform $f_R^*(s)$. Let t_D be the delay between when user 2's handset rings and when user 2 accepts the call, which is a random variable with the density function $f_D(\cdot)$, the mean $1/\lambda_D$, the variance V_D, and the Laplace transform $f_D^*(s)$. At Step 1.3 of RCB-I$_2$, callback may repeat if user 1 has not terminated the first call

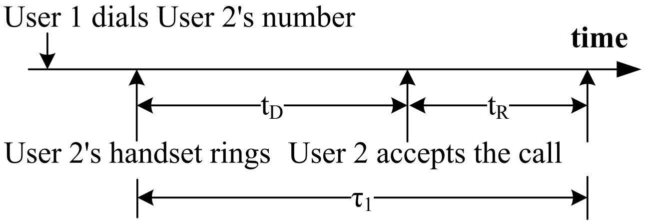

Fig. 4. Timing diagram for the 3GPP call setup.

(i.e., the RELEASE COMPLETE message has not arrived at user 1 in Path 3 of Figure 2). Let N be the number of callbacks performed by RCB-I$_2$ before the call is connected (in Figure 3, $N = 2$). Let $t_{I,i}$ and $t_{R,i}$ be the IAM/SETUP and the REL/RELEASE COMPLETE message delays for the ith callback of local paths (5)→(4)→(6)→(2)→(1) (Path 4 in Figure 2) and (1)→(2)→(6)→(4)→(5) in Figure 1 (Path 5 in Figure 2), respectively. Let t_A be the ANM/CONNECT message delay of local path (1)→(2)→(6)→(4)→(5) in Figure 1 (Path 5 in Figure 2). We assume that $t_{I,i}$, $t_{R,i}$, and t_A are independent and identically distributed random variables with the same density function $f_I(\cdot)$, the mean $1/\lambda_I$, the variance V_I, and the Laplace transform $f_I^*(s)$.

We compare RCB with the 3GPP procedure by measuring the call setup delays after the IAM/SETUP message arrives at user 2 (i.e., after the end of Path 1 in Figure 2; note that the delays of Path 1 are the same for both procedures):

- **τ_1 (The 3GPP tromboning call setup delay):** When user accepts the call, his/her handset sends the ANM/CONNECT message of international path (5)→(4)→(3)→(2)→(1) in Figure 1. Because this ANM/CONNECT message delay is basically the same as the REL/RELEASE COMPLETE message delay t_R, τ_1 can be expressed as $\tau_1 = t_D + t_R$ (as illustrated in Figure 4) and its expected value is

$$E[\tau_1] = E[t_D] + E[t_R] = \frac{\lambda_D + \lambda_R}{\lambda_D \lambda_R} \tag{1}$$

- **τ_2 (Call setup delay where both users 1 and 2 install the RCB software):** From Figure 3, $E[\tau_2]$ includes $E[t_D]$ (user 2 accepts the call), $(E[N]-1)(E[t_{I,i}] + E[t_{R,i}])$ ($N-1$ unsuccessful callbacks), $E[t_{I,i}]$ (the successful callback), and $E[t_A]$ (RCB-O$_1$ accepts the local callback and replies ANM/CONNECT message). Therefore,

$$\begin{aligned} E[\tau_2] &= E[t_D] + (E[N]-1)(E[t_{I,i}] + E[t_{R,i}]) \\ &\quad + E[t_{I,i}] + E[t_A] \\ &= \frac{1}{\lambda_D} + \frac{2E[N]}{\lambda_I} \end{aligned} \tag{2}$$

In the following subsections, we consider two scenarios for deriving $E[\tau_2]$:

Scenario 1. Assume that (i) t_R is exponentially distributed with the mean $1/\lambda_R$, and (ii) t_D and $t_{I,i}$ have arbitrary distributions.

Scenario 2. Assume that (i) t_R has arbitrary distribution, and (ii) t_D and $t_{I,i}$ are exponentially distributed with the means $1/\lambda_D$ and $1/\lambda_I$, respectively.

In Scenarios 1 and 2, although the realistic signaling delay distribution may not be the exponential distribution, the exponential distribution does provide the mean value analysis for a primary study on the trends of the signaling delay impact. Also, analytic results based on exponential assumption are used to validate the simulation experiments, and the validated simulation model can be used to study realistic traffic distribution measured from the commercial operation.

To simplify our discussion without loss of generality, we ignore the timers $T1$, $T2$, and $T3$ (which means that τ_2 is not limited by $T1$, $T2$, and $T3$, and the analysis actually favors the 3GPP call setup).

Before deriving $E[\tau_2]$, we define a random variable

$$t_{1,n} = t_{I,n} + \sum_{i=1}^{n-1} (t_{I,i} + t_{R,i}) \tag{3}$$

with the Laplace transform $f_{1,n}^*(s)$. From (3),

$$f_{1,n}^*(s) = [f_I^*(s)]^{2n-1} \tag{4}$$

From Figure 3 and (3), we define

$$t_{2,n} = t_D + t_{1,n} \tag{5}$$

with the density function $f_{2,n}(\cdot)$. From (4) and (5), the Laplace transform of $f_{2,n}(\cdot)$ is derived as

$$f_{2,n}^*(s) = f_D^*(s)[f_I^*(s)]^{2n-1} \tag{6}$$

In this section, $t_{2,n}$ and t_R are used to derive $E[N]$.

A. Scenario 1: Exponential t_R and Arbitrary t_D, $t_{I,i}$, $t_{R,i}$, and t_A

Let N_1 and $\tau_{2,1}$ be the N number and the τ_2 delay in Scenario 1, respectively. To obtain (2), we first derive $E[N_1]$. Let $\Pr[N_1 \le n]$ be the probability that the number of callbacks performed by RCB-I$_2$ is less than or equal to n in Scenario 1. From Figure 3 and (5), it is clear that $\Pr[N_1 \le n] = \Pr[t_{2,n} > t_R]$, which is derived as

$$\begin{aligned} \Pr[t_{2,n} > t_R] &= \int_{t_{2,n}=0}^{\infty} f_{2,n}(t_{2,n}) \int_{t_R=0}^{t_{2,n}} f_R(t_R)\, dt_R\, dt_{2,n} \\ &= \int_{t_{2,n}=0}^{\infty} f_{2,n}(t_{2,n})(1 - e^{-\lambda_R t_{2,n}})\, dt_{2,n} \\ &= 1 - f_D^*(\lambda_R)[f_I^*(\lambda_R)]^{2n-1} \end{aligned} \tag{7}$$

In Figure 3, RCB-I$_2$ performs one callback if $t_{2,1} > t_R$. From (7), we have

$$\begin{aligned} \Pr[N_1 = 1] &= \Pr[t_{2,1} > t_R] \\ &= 1 - f_D^*(\lambda_R) f_I^*(\lambda_R) \end{aligned} \tag{8}$$

For $n \ge 2$, from (7), $\Pr[N_1 = n]$ is derived as

$$\begin{aligned} \Pr[N_1 = n] &= \Pr[N_1 \le n] - \Pr[N_1 \le n-1] \\ &= f_D^*(\lambda_R)[f_I^*(\lambda_R)]^{2n-3}(1 - [f_I^*(\lambda_R)]^2) \end{aligned} \tag{9}$$

From (8) and (9),

$$\begin{aligned} E[N_1] &= \sum_{n=1}^{\infty} n \Pr[N_1 = n] \\ &= 1 + \frac{f_D^*(\lambda_R) f_I^*(\lambda_R)}{1 - [f_I^*(\lambda_R)]^2} \end{aligned} \tag{10}$$

Assume that $t_{I,i}$ is a Gamma random variable with the mean $1/\lambda_I$, the variance V_I, and the Laplace transform

$$\begin{aligned} f_I^*(s) &= G^*(\lambda_I, V_I) \\ &= \left(\frac{1}{V_I\lambda_I s+1}\right)^{\frac{1}{V_I\lambda_I^2}} \end{aligned} \tag{11}$$

Likewise, assume that t_D is a Gamma random variable with the mean $1/\lambda_D$, the variance V_D, and the Laplace transform $G^*(\lambda_D, V_D)$. We consider the Gamma distribution because this distribution is widely used in telecom modeling; see [14] and the references there in.

From (10) and (11), $E[N_1]$ is re-written as

$$\begin{aligned} E[N_1] &= \frac{(V_I\lambda_I\lambda_R+1)^{\frac{1}{V_I\lambda_I^2}}}{\left[(V_I\lambda_I\lambda_R+1)^{\frac{2}{V_I\lambda_I^2}}-1\right](V_D\lambda_D\lambda_R+1)^{\frac{1}{V_D\lambda_D^2}}} \\ &\quad +1 \end{aligned} \tag{12}$$

From (2) and (12),

$$\begin{aligned} E[\tau_{2,1}] &= \frac{(V_I\lambda_I\lambda_R+1)^{\frac{1}{V_I\lambda_I^2}}}{\left[(V_I\lambda_I\lambda_R+1)^{\frac{2}{V_I\lambda_I^2}}-1\right](V_D\lambda_D\lambda_R+1)^{\frac{1}{V_D\lambda_D^2}}} \\ &\quad \times\frac{2}{\lambda_I}+\frac{1}{\lambda_D}+\frac{2}{\lambda_I} \end{aligned} \tag{13}$$

B. Scenario 2: Arbitrary t_R and Exponential t_D, $t_{I,i}$, $t_{R,i}$, and t_A

Let N_2 and $\tau_{2,2}$ be the N number and the τ_2 delay in Scenario 2, respectively. We first derive $E[N_2]$. Because $t_{I,i}$ and $t_{R,i}$ are identically exponential random variables, from (3), $t_{1,n}$ has an Erlang distribution with the mean $(2n-1)/\lambda_I$ and the density function

$$f_{1,n}(t_{1,n}) = \frac{\lambda_I^{2n-1}t_{1,n}^{2n-2}e^{-\lambda_I t_{1,n}}}{(2n-2)!} \tag{14}$$

From (5) and (14), the density function $f_{2,n}(\cdot)$ for $t_{2,n}$ is derived as (15).

Similar to the derivation for $E[N_1]$, $E[N_2]$ is derived as follows. For $\lambda_D \neq \lambda_I$, $E[N_2]$ is derived as (16). For $\lambda_D = \lambda_I$,

$$\begin{aligned} E[N_2] &= \sum_{i=1}^{\infty}\left\lceil\frac{i+1}{2}\right\rceil\left[\frac{(-\lambda_I)^i}{i!}\right]\left[\left.\frac{d^i f_R^*(s)}{ds^i}\right|_{s=\lambda_I}\right] \\ &\quad +f_R^*(\lambda_I) \end{aligned} \tag{17}$$

Assume that t_R is a Gamma random variable with the mean $1/\lambda_R$, the variance V_R, and the Laplace transform $G^*(\lambda_R, V_R)$. Then $E[N_2]$ is re-written as follows. For $\lambda_D \neq \lambda_I$, $E[N_2]$ is re-written as (18). Note that in (18), when $j=0$, $\prod_{k=1}^{j}$ represents an empty product, and its value is equal to 1. For $\lambda_D = \lambda_I$,

$$\begin{aligned} E[N_2] &= \left(\frac{1}{V_R\lambda_R\lambda_I+1}\right)^{\frac{1}{V_R\lambda_R^2}}+\sum_{i=1}^{\infty}\left\lceil\frac{i+1}{2}\right\rceil \\ &\quad \times\left[\frac{(-\lambda_I V_R\lambda_R)^i\prod_{j=1}^{i}\left(-\frac{1}{V_R\lambda_R^2}-j+1\right)}{i!(V_R\lambda_R\lambda_I+1)^{\frac{1}{V_R\lambda_R^2}+i}}\right] \end{aligned} \tag{19}$$

From (18) and (19), (2) is re-written follows. For $\lambda_D \neq \lambda_I$, $E[\tau_{2,2}]$ is re-written as (20). For $\lambda_D = \lambda_I$,

$$\begin{aligned} E[\tau_{2,2}] &= \frac{1}{\lambda_D}+\left(\frac{2}{\lambda_I}\right)\left(\frac{1}{V_R\lambda_R\lambda_I+1}\right)^{\frac{1}{V_R\lambda_R^2}} \\ &\quad +\sum_{i=1}^{\infty}\left\lceil\frac{i+1}{2}\right\rceil\left[\frac{2(-\lambda_I V_R\lambda_R)^i}{\lambda_I i!(V_R\lambda_R\lambda_I+1)^{\frac{1}{V_R\lambda_R^2}+i}}\right] \\ &\quad \times\left[\prod_{j=1}^{i}\left(-\frac{1}{V_R\lambda_R^2}-j+1\right)\right] \end{aligned} \tag{21}$$

Equations (13), (20), and (21) are validated against the discrete event simulation experiments (following the same methodology as the one developed in [10]), which show that the discrepancies between the analytic and simulation results are within 0.1%.

V. NUMERICAL EXAMPLES

This section investigates the call setup delays of RCB and the standard 3GPP procedure. Define the signal cost improvement α of RCB over the 3GPP procedure as

$$\alpha = \frac{E[\tau_1]-E[\tau_2]}{E[\tau_1]} \tag{22}$$

Because the delay of an international trunk is typically one to three times longer than that for a local trunk, it is reasonable to assume that $2E[t_{I,i}] \leq E[t_R] \leq 4E[t_{I,i}]$. Also, in telecom operation, $E[t_D] \geq 5[t_{I,i}]$. Figure 5 shows that α increases as $E[t_R]/E[t_{I,i}]$ increases. From the above $E[t_R]$ and $E[t_D]$ assumptions, it is very likely that $t_D + t_{I,i} > t_R$. In this case, $\tau_2 = t_D + t_{I,i} + t_A = t_D + 2t_{I,i}$ (see Figure 3), and from (22),

$$\alpha = \frac{E[t_R]-2E[t_{I,i}]}{E[t_D]+E[t_R]} \tag{23}$$

In (23), α increases as $E[t_R]/E[t_{I,i}]$ increases.

Figure 5 (a) indicates that α decreases as V_D increases. For a fixed $E[t_D]$ value, when V_D increases, there are much more short t_D periods than long t_D periods. For short t_D, it is likely that $t_D + t_{I,1} < t_R$, and these short t_D periods result in more callbacks (i.e., larger $E[N]$). Since $E[\tau_2]$ is an increasing function of $E[N]$, $E[\tau_2]$ increases as V_D increases. On the other hand, $E[\tau_1]$ is not sensitive to the change of V_D. From (22), α decreases as V_D increases. Similarly, Figure 5 (b) shows that when V_I increases, α decreases.

Figure 5 (c) shows that α decreases as V_R increases. Because $E[t_R]$ is less than $E[t_D] + E[t_{I,i}]$, when V_R is

$$\begin{aligned} f_{2,n}(t_{2,n}) &= \int_{t_{1,n}=0}^{t_{2,n}} \lambda_D e^{-\lambda_D(t_{2,n}-t_{1,n})} \left[\frac{\lambda_I^{2n-1} t_{1,n}^{2n-2} e^{-\lambda_I t_{1,n}}}{(2n-2)!}\right] dt_{1,n} \\ &= \begin{cases} \left\{ e^{-\lambda_I t_{2,n}} \sum_{i=0}^{2n-2} \left[\frac{(-1)^i(\lambda_D-\lambda_I)^i t_{2,n}^i}{i!}\right] - e^{-\lambda_D t_{2,n}} \right\} \left[\frac{\lambda_D \lambda_I^{2n-1}}{(\lambda_D-\lambda_I)^{2n-1}}\right], & \text{if } \lambda_D \neq \lambda_I \\ \frac{\lambda_I^{2n} t_{2,n}^{2n-1} e^{-\lambda_I t_{2,n}}}{(2n-1)!}, & \text{if } \lambda_D = \lambda_I \end{cases} \end{aligned} \tag{15}$$

$$\begin{aligned} E[N_2] &= \frac{\lambda_D f_R^*(\lambda_I) - \lambda_I f_R^*(\lambda_D)}{\lambda_D - \lambda_I} + \sum_{n=2}^{\infty} n \left[\frac{\lambda_D \lambda_I^{2n-3}}{(\lambda_D-\lambda_I)^{2n-3}}\right] \left\{ \sum_{i=0}^{2n-2} \sum_{j=0}^{i} \left[\frac{(\lambda_D-\lambda_I)^{i-2}(-1)^{i-j}}{j!\lambda_I^{i-j-1}}\right] \left[\frac{d^j f_R^*(s)}{ds^j}\bigg|_{s=\lambda_I} \right] \right. \\ &\left. - \sum_{i=0}^{2n-4} \sum_{j=0}^{i} \left[\frac{(\lambda_D-\lambda_I)^{i}(-1)^{i-j}}{j!\lambda_I^{i-j+1}}\right] \left[\frac{d^j f_R^*(s)}{ds^j}\bigg|_{s=\lambda_I} \right] - \left[\left(\frac{\lambda_I}{\lambda_D-\lambda_I}\right)^2 - 1\right] \left[\frac{f_R^*(\lambda_D)}{\lambda_D}\right] \right\} \end{aligned} \tag{16}$$

$$\begin{aligned} E[N_2] &= \left(\frac{1}{\lambda_D-\lambda_I}\right) \left[\lambda_D \left(\frac{1}{V_R\lambda_R\lambda_I+1}\right)^{\frac{1}{V_R\lambda_R^2}} - \lambda_I \left(\frac{1}{V_R\lambda_R\lambda_D+1}\right)^{\frac{1}{V_R\lambda_R^2}} \right] + \sum_{n=2}^{\infty} n \left[\frac{\lambda_D \lambda_I^{2n-3}}{(\lambda_D-\lambda_I)^{2n-3}}\right] \left\{ \sum_{i=0}^{2n-2} \sum_{j=0}^{i} \right. \\ &\times \left[\frac{(\lambda_D-\lambda_I)^{i-2}(-1)^{i-j}(V_R\lambda_R)^j}{j!\lambda_I^{i-j-1}(V_R\lambda_R\lambda_I+1)^{\frac{1}{V_R\lambda_R^2}+j}}\right] \left[\prod_{k=1}^{j}\left(-\frac{1}{V_R\lambda_R^2} - k + 1\right)\right] - \sum_{i=0}^{2n-4} \sum_{j=0}^{i} \left[\frac{(\lambda_D-\lambda_I)^{i}(-1)^{i-j}(V_R\lambda_R)^j}{j!\lambda_I^{i-j+1}(V_R\lambda_R\lambda_I+1)^{\frac{1}{V_R\lambda_R^2}+j}}\right] \\ &\left. \times \left[\prod_{k=1}^{j}\left(-\frac{1}{V_R\lambda_R^2} - k + 1\right)\right] - \left(\frac{1}{\lambda_D}\right) \left[\left(\frac{\lambda_I}{\lambda_D-\lambda_I}\right)^2 - 1\right] \left(\frac{1}{V_R\lambda_R\lambda_D+1}\right)^{\frac{1}{V_R\lambda_R^2}} \right\} \end{aligned} \tag{18}$$

$$\begin{aligned} E[\tau_{2,2}] &= \frac{1}{\lambda_D} + \left[\frac{2}{\lambda_I(\lambda_D-\lambda_I)}\right] \left[\lambda_D \left(\frac{1}{V_R\lambda_R\lambda_I+1}\right)^{\frac{1}{V_R\lambda_R^2}} - \lambda_I \left(\frac{1}{V_R\lambda_R\lambda_D+1}\right)^{\frac{1}{V_R\lambda_R^2}} \right] + 2\sum_{n=2}^{\infty} n \left[\frac{\lambda_D \lambda_I^{2n-4}}{(\lambda_D-\lambda_I)^{2n-3}}\right] \\ &\times \left\{ \sum_{i=0}^{2n-2} \sum_{j=0}^{i} \left[\frac{(\lambda_D-\lambda_I)^{i-2}(-1)^{i-j}(V_R\lambda_R)^j}{j!\lambda_I^{i-j-1}(V_R\lambda_R\lambda_I+1)^{\frac{1}{V_R\lambda_R^2}+j}}\right] \left[\prod_{k=1}^{j}\left(-\frac{1}{V_R\lambda_R^2} - k + 1\right)\right] - \sum_{i=0}^{2n-4} \sum_{j=0}^{i} \right. \\ &\times \left[\frac{(\lambda_D-\lambda_I)^{i}(-1)^{i-j}(V_R\lambda_R)^j}{j!\lambda_I^{i-j+1}(V_R\lambda_R\lambda_I+1)^{\frac{1}{V_R\lambda_R^2}+j}}\right] \left[\prod_{k=1}^{j}\left(-\frac{1}{V_R\lambda_R^2} - k + 1\right)\right] - \left(\frac{1}{\lambda_D}\right) \left[\left(\frac{\lambda_I}{\lambda_D-\lambda_I}\right)^2 - 1\right] \\ &\left. \times \left(\frac{1}{V_R\lambda_R\lambda_D+1}\right)^{\frac{1}{V_R\lambda_R^2}} \right\} \end{aligned} \tag{20}$$

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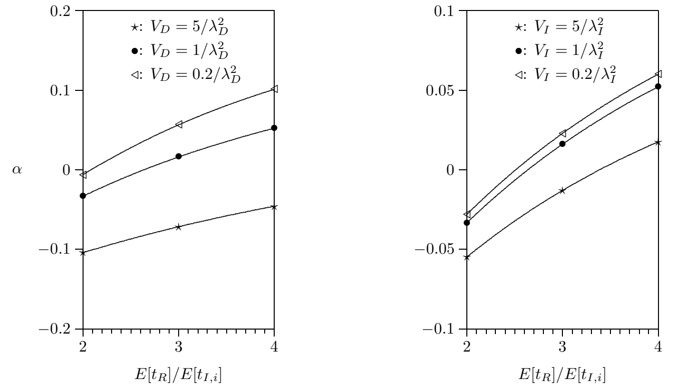
small, it is more likely that $t_R < t_D + t_{I,i}$ and RCB-I only performs one callback (small $E[N]$ is observed). However, when t_R becomes irregular (i.e., V_R increases), more long and short t_R periods are observed. The long t_R periods result in $t_R > t_D + t_{I,i}$ and incur large $E[N]$. Therefore, from (2) and (22), α decreases as V_R increases.

Figure 5 (d) indicates that α increases as $E[t_D]/E[t_{I,i}]$ increases. From Figure 3, it is clear that $E[N]$ decreases as $E[t_D]/E[t_{I,i}]$ increases, and the local callback delay (i.e., $2E[N]/\lambda_I$ in (2)) decreases while the international message delay (i.e., $1/\lambda_R$ in (1)) remains the same. From (1), (2), and (22), α increases as $E[t_D]/E[t_{I,i}]$ increases.

In summary, Figure 5 indicates that by varying the parameters of the delay distributions, RCB may outperform or underperform the 3GPP procedure in terms of call setup signaling. However, the performance discrepancies between RCB and the 3GPP procedure are within 10%. We note that the above results are consistent with the measurements in a Taiwan's commercial telecom network.

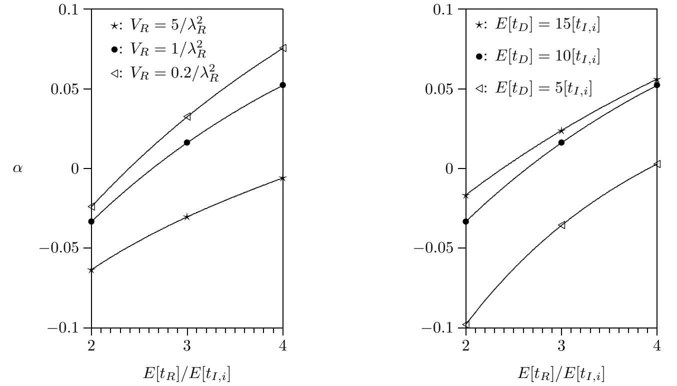
VI. CONCLUSION

This paper proposed *Roamer's CallBack* algorithm (RCB) exercised at the handset to solve tromboning/triangular problem. Our solution does not require to add/modify network



(a) $E[t_D] = 10E[t_{I,i}]$, $V_I = 1/\lambda_I^2$, and $V_R = 1/\lambda_R^2$

(b) $E[t_D] = 10E[t_{I,i}]$, $V_D = 1/\lambda_D^2$, and $V_R = 1/\lambda_R^2$



(c) $E[t_D] = 10E[t_{I,i}]$, $V_D = 1/\lambda_D^2$, and $V_I = 1/\lambda_I^2$

(d) $V_D = 1/\lambda_D^2$, $V_I = 1/\lambda_I^2$, and $V_R = 1/\lambda_R^2$

Fig. 5. Comparison of RCB and the 3GPP procedure.

nodes in the existing telecom network. We conducted analytic modeling and simulation experiments to show that RCB is effective in call setup signaling. Performance study indicates that if both call parties install the RCB software, the call setup delay is similar to that of the 3GPP procedure (within 10% discrepancy). That is, RCB eliminate 100% international trunk cost with the similar call setup delay as compared with the 3GPP procedure, which is quite acceptable in commercial operation. RCB works for both the fixed and the mobile callers, where a fixed caller is the same as a non-roaming mobile user. For the scenario when the caller is roaming, the RCB callback delay may be twice as the international message delay. However, based on the statistics from mobile operators, this scenario seldom occurs (less than 1% excluding when the caller ID is withheld). Therefore, RCB is an effective solution for international roaming, and is now a pending US patent of Chunghwa Telecom.

APPENDIX
NOTATION

The notation used in this paper is summarized below.

- τ_1: the 3GPP tromboning call setup delay.
- τ_2: the call setup delay where both call parties install the RCB software.
- t_R: the REL/RELEASE COMPLETE message delay of international path (5)→(4)→(3)→(2)→(1) in Figure 1.
- t_D: the delay between when user 2's handset rings and when user 2 accepts the call.
- $t_{I,i}$: the IAM/SETUP message delay for ith callback of local path (5)→(4)→(6)→(2)→(1) in Figure 1.
- $t_{R,i}$: the REL/RELEASE COMPLETE message delay for ith callback of local path (1)→(2)→(6)→(4)→(5) in Figure 1.
- t_A: the ANM/CONNECT message delay of local path (1)→(2)→(6)→(4)→(5) in Figure 1.
- N: the number of the callbacks performed by the user 2's RCB-I before the call is connected.
- $1/\lambda_R = E[t_R]$: mean REL/RELEASE COMPLETE message delay of the international path
- $1/\lambda_D = E[t_D]$: mean delay between when user 2's handset rings and when user 2 accepts the call
- $1/\lambda_I = E[t_{I,i}]$: mean IAM/SETUP message delay of local path
- V_R: the variance for the t_R distribution
- V_D: the variance for the t_D distribution
- V_I: the variance for the t_I distribution
- $f_R(\cdot)$: the density function for the t_R distribution
- $f_D(\cdot)$: the density function for the t_D distribution
- $f_I(\cdot)$: the density function for the $t_{I,i}$ distribution
- $f_R^*(s)$: the Laplace transform for the t_R distribution
- $f_D^*(s)$: the Laplace transform for the t_D distribution
- $f_I^*(s)$: the Laplace transform for the $t_{I,i}$ distribution

ACKNOWLEDGMENT

The authors would like to thank the three anonymous reviewers. Their comments have significantly improved the quality of this paper.

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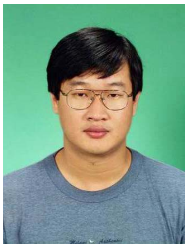

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