using $\mathbf{A}_1 = \mathbf{Q}_1$, we obtain

$$\mathbf{B}_1 = \mathbf{C}_1. \tag{A7}$$

From (A4) and (A7), we have

$$\mathbf{B}_1 = \mathbf{B}(1:N-1, 1:N-1). \tag{A8}$$

Repeating the foregoing process, we similarly obtain

$$\mathbf{B}_j = \mathbf{B}(1:N-j, 1:N-j), j = 1, 2, \ldots, N-1. \tag{A9}$$

If the LDL^H factorization of $\mathbf{Q}_j^{-1}$ is $\mathbf{Q}_j^{-1} = \mathbf{L}_j\mathbf{D}_j\mathbf{L}_j^H$, then $\mathbf{Q}_j = \mathbf{U}_j\mathbf{D}_j^{-1}\mathbf{U}_j^H$, where $\mathbf{U}_j = (\mathbf{L}_j^H)^{-1}$. The diagonal elements of $\mathbf{D}_j$ can be obtained as $D_j(i,i) = B_j^{-2}(i,i)$, where $B_j(i,i)$ is the diagonal element of $\mathbf{B}_j$. From (A9), we obtain

$$\mathbf{D}_j = \mathbf{D}(1:N-j, 1:N-j). \tag{A10}$$

$\mathbf{U}_j$ can be obtained as $\mathbf{U}_j = \mathbf{B}_j\mathbf{D}'_j$, where $\mathbf{D}'_j$ is a diagonal matrix with elements given by $D'_j(i,i) = \sqrt{D_j(i,i)},\ j = 1, 2, \ldots, N-j$. From (A9) and (A10), we obtain

$$\mathbf{U}_j = \mathbf{U}(1:N-j, 1:N-j). \tag{A11}$$

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Reducing International Call Costs for Roamer to Roamer Calls

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***Abstract*—Existing mobile telecom operators allow subscribers to receive mobile phone services when they roam in other countries. However, call setup to an international roaming subscriber is indirectly routed through the home network of the subscriber, which results in the usage of two expensive international telephone trunks. In this paper, we propose a plug-in roaming gateway to avoid the international trunk connections. Our solution is especially attractive when both call parties are roamers.**

***Index Terms*—International roaming, mobile telecom service, mobility management, tromboning.**

I. Introduction

Mobile telecom operators offer telephone services when the subscribers roam in other countries. However, a call setup to a roaming mobile subscriber may result in two expensive international trunk connections. We use the *Universal Mobile Telecommunications System* (UMTS) as an example to describe this issue. Consider the following scenario where a subscriber Jenny [see Fig. 1(A)] of Taiwan (*home network*) roams in the U.S. (*visited network*). When Jenny arrives in the U.S., she turns on her handset that connects to a *Mobile Switching Center* [MSC1; see Fig. 1(B)]. Following the mobile roaming protocol [1], the handset sends a registration message to its Home Location Register or *Home Subscriber Server* [HSS; Fig. 1(H)] to indicate that it has moved to the U.S. The registration message is delivered through the U.S. mobile/fixed networks [Network-U; see Fig. 1(C)], the U.S. *International Switching Center* [ISC-U; see Fig. 1(D)], the Taiwan *International Switching Center* [ISC-T; see Fig. 1(E)], the Taiwan fixed/mobile networks [Network-T; see Fig. 1(F)], and the *Gateway Mobile Switching Center* of Jenny [GMSC; see Fig. 1(G)]. In this path, ISC-U and ISC-T are connected through international trunks.

When John in the U.S. [see Fig. 1(I)] calls Jenny, the call setup message flow consists of two parts:

Step A.1. The call setup message is sent from John to Jenny through path (I) → (J) → (C) → (D) → (E) → (F) → (G) → (H) → (G) → (F) → (E) → (D) → (C) → (B) → (A) in Fig. 1. In this step, the HSS is queried to identify the switch (i.e., MSC1) that connects to Jenny.

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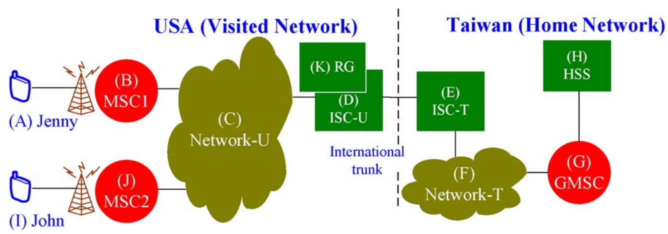

Fig. 1. Mobile telecom network with international roaming.

Step A.2. Jenny replies if the call is accepted or rejected through the message path (A) → (B) → (C) → (D) → (E) → (F) → (G) → (F) → (E) → (D) → (C) → (J) → (I).

The voice path is (I)–(J)–(C)–(D)–(E)–(F)–(G)–(F)–(E)–(D)–(C)–(B)–(A), which results in two international voice trunks (i.e., two (D)–(E) links). This is so called *tromboning* problem. Skype and other voice over Internet protocol solutions [2], [3] resolve tromboning problem for Internet users. However, they do not work for E.164 telephone numbers because a GMSC is controlled by the telecom network and is always connected in the voice call path. To resolve tromboning issue, *Third-Generation Partnership Project* (3GPP) 22.079 [4] describes a solution that requires John to dial a special code, e.g., "#0." It also requires a roaming agreement between the home and the visiting mobile operators, which is not attractive to the mobile operators. In [5], we proposed a solution that does not need a roaming agreement between mobile operators at the cost of assigning permanent local telephone numbers to Jenny. In this paper, we propose a new approach to eliminate international tromboning, which does not require a roaming agreement and does not need to assign permanent local phone numbers to the roamers.

II. Roaming Group Solution

Our solution applies to a group of users. The users first establish a *roaming group*, and all members in this group can make calls to other members (who are roamers) by avoiding the international tromboning links. The roaming group can be easily preset and dynamically modified through a website or a handset. During the setup of this group, the roaming software is downloaded to every member's handset. Software download can be transparently executed over the air [5].

This solution implements a *Roaming Gateway* [RG; see Fig. 1(K)] with the following features:

1) The RG is a standard telecom switch which is preferably colocated with the ISC [see Fig. 1(D)]. This gateway is assigned a block of telephone numbers, say, from 443-8700000 to 443-8799999 in the U.S. (if the RG is installed in the U.S.). When someone dials any number in this telephone number block, the call will be routed to the RG following the standard SS7 protocol [1].
2) The RG maintains a mapping table that maps the telephone number of a roamer (e.g., +886-910111111 for Jenny) to a temporary local telephone number 443-87xxxxx in the block.
3) This solution implements the RG registration and the call setup procedures. Two numbers of the RG are specifically used for registration (e.g., 443-8700000) and deregistration (e.g., 443-8700001). The RG utilizes the short message protocol [1] in RG registration and deregistration procedures.

Consider a roaming group consisting of two members Jenny and John, where Jenny is from Taiwan (with phone number +886-910111111). Suppose that the RG is installed in the U.S. When Jenny roams to the U.S., her handset first conducts the standard 3GPP registration back to the HSS, as described in Section I, and then performs RG registration as follows:

Step B.1. The roaming software of Jenny's handset detects that she has roamed to a visited mobile network (see [5] for implementation of this feature). Then, it performs the RG registration by automatically dialing RG's registration number 443-8700000, which results in an SS7 *Initial Address Message* (IAM) message sent to the RG through path (A) → (B) → (C) → (K) in Fig. 1. Jenny's phone number is indicated in the caller ID of the IAM message.

Step B.2. When the RG receives the IAM message, it retrieves Jenny's phone number in the caller ID of the IAM and creates an entry (+886-910111111, 443-8711111) in its mapping table. The number 443-8711111 is temporarily assigned.

Step B.3. The RG returns an SS7 *Address Complete Message* (ACM) with a busy flag. Jenny's roaming software terminates the call setup, and the registration is complete.

Step B.4. The RG sends a short message with the mapping (+886-910111111, 443-8711111) to all members in Jenny's roaming group. When the roaming software of these handsets receives the short message, it creates an entry (+886-910111111, 443-8711111).

When Jenny moves from the U.S. to another country, her roaming software will automatically dial the "de-registration" phone number (i.e., +1-4438700001). When the RG receives this IAM message, it retrieves the caller ID (+886-910111111) and uses it to delete Jenny's entry in its mapping table. The RG will send a short message to all members of Jenny's roaming group to indicate that 443-8711111 is no longer assigned to Jenny. Note that this procedure is different from 3GPP location cancellation procedure.

Suppose that John calls Jenny when both of them are in the U.S. If John (in Jenny's roaming group) is a roamer with phone number +886-910222222, then both the RG and Jenny handsets will have an entry (+886-910222222, 443-8722222). The call setup procedure works as follows:

Step C.1. When John dials Jenny's phone number +886-910111111, the roaming software of his handset uses this number to retrieve the local phone number 443-8711111 and actually dials this local number.

Step C.2. The IAM message is sent to the RG through path (I) → (J) → (C) → (K) in Fig. 1. From the destination number 443-8711111 of the IAM message, the RG retrieves Jenny's phone number +886-910111111.

Step C.3. The RG replaces the destination address of the IAM message by +886-910111111. Then, this message is sent to Jenny through the standard international roaming call setup. The message delivery path is (K) → (D) → (E) → (F) → (G) → (H) → (G) → (F) → (E) → (D) → (C) → (B) → (A).

Step C.4. When MSC1 receives the IAM message, the caller ID +886-910222222 is displayed to Jenny. When Jenny picks up the phone, the handset first rejects the call. Then the roaming software uses the caller ID to retrieve John's temporary local phone number 443-8722222 in its mapping table and initiates a callback to 443-8722222.

Step C.5. When the RG receives the ACM message, it will wait for Jenny's callback (the IAM) for a period T. The IAM message is delivered to the RG through path (A) → (B) → (C) → (K) in Fig. 1.

Step C.6. When the RG receives the IAM, it bridges the two setup calls in Steps C.2 and C.5. The voice path is (I)–(J)–(C)–(K)–(C)–(B)–(A).

If John is a U.S. user (nonroaming mobile user) with phone number 443-8222222, the call setup procedure from John to Jenny (a roamer to the U.S.) works as follows:

Step D.1. When John dials Jenny's phone number +886-910111111, the local phone number 443-8711111 is dialed, as in Step C.1.

Step D.2. The IAM message is sent to the RG that retrieves Jenny's phone number +886-910111111, as in Step C.2.

Step D.3. The RG replaces the destination address and sends the message to Jenny, as in Step C.3.

Step D.4. Jenny's handset receives the call setup request. Suppose that Jenny picks up the call. Unlike Step C.4, the roaming software first rejects the call but then initiates a new call directly back to John through MSC1 that issues an IAM with the destination address 443-8222222.

Step D.5. When MSC2 receives the ACM message, it informs John's handset. John's handset expects to receive a callback from Jenny for a period T. The callback is set up from Jenny to John through path (A) $\rightarrow$ (B) $\rightarrow$ (C) $\rightarrow$ (J) $\rightarrow$ (I) in Fig. 1. The voice path is (I)–(J)–(C)–(B)–(A). Note that the IAM message may arrive at John earlier than the ACM message does. In this case, John's handset directly accepts the callback. If the period T expires, Jenny is assumed to reject this call (and will not call back), and the call setup is terminated.

The above call setup procedure is basically a callback service, where Jenny's handset first rejects John's call and then calls back to John to avoid expensive international tromboning links. Through the roaming software in the handsets, both John and Jenny never notice the "callback action." Even if John is not in Jenny's roaming group, this procedure still works. The differences are that the destination number of the IAM in Step D.1 is +886-910111111, and the message is delivered directly to Jenny without the involvement of the RG. Also, in Step D.5, John is actually notified that his call is rejected by Jenny, and then, he needs to actually press the button of his handset to accept the subsequent callback from Jenny.

III. Discussion and Concluding Remarks

Based on the description in the previous section, when a roamer Jenny travels from the home network (e.g., Taiwan) to the visited network (e.g., the U.S.), the roaming group solution can significantly reduce the cost of any call from a user John in the visited network to Jenny.

For the voice path, indirect routing (through the home network) of the 3GPP procedure is avoided in the roaming group solution, and therefore, the voice quality is much better than that for the 3GPP procedure.

It is also clear that call setup is faster in the roaming group approach than that in the 3GPP procedure. An exact call setup signaling delay comparison can be conducted as follows: When John calls Jenny, the IAM message delay is basically the same for both the 3GPP procedure (Step A.1) and the roaming group procedure (Steps C.1–C.3 or Steps D.1–D.3). However, the cost for the ACM (and the subsequent Answer message [1]) signal delay in the 3GPP procedure (Step A.2) is different from the callback delay in the roaming group procedure (Steps C.4–C.6 or Steps D.4–D.5). Note that the delay in which the roaming software rejects the call (Step C.4 or Step D.4) does not affect the total call setup time because the roaming software performs the callback in parallel with the rejection.

Let the callback delay in Steps C.4–C.6 or Steps D.4–D.5 be t_1, which is a random variable with density function $f_1(t_1)$, the mean $1/\lambda_1$, the variance V_1, and the Laplace transform $f_1^*(s)$. The signal delay in Step A.2 consists of two periods t_2 ((A) $\rightarrow$ (B) $\rightarrow$ (C) $\rightarrow$ (D) $\rightarrow$ (E) $\rightarrow$ (F) $\rightarrow$ (G)) and t_3 ((G) $\rightarrow$ (F) $\rightarrow$ (E) $\rightarrow$ (D) $\rightarrow$ (C) $\rightarrow$ (J) $\rightarrow$ (I)). Note that it is appropriate to assume that t_2 and t_3 have the same distribution. Let t_2 be a random variable with density function $f_2(t_2)$, the mean $1/\lambda_2$, the variance V_2, and the Laplace transform $f_2^*(s)$.

Suppose that t_1 is exponentially distributed with the mean $1/\lambda_1$ and that t_2 has an arbitrary distribution. Let $t_4 = t_2 + t_3$ be a random variable with density function $f_4(t_4)$; then, the Laplace transform $f_4^*(s) = [f_2^*(s)]^2$. Let $\Pr[t_1 < t_4]$ be the probability that call setup in the roaming group approach is faster than that in the 3GPP procedure. This probability is derived as

$$\begin{aligned}\Pr[t_1 < t_4] &= \int_{t_4=0}^{\infty} f_4(t_4) \int_{t_1=0}^{t_4} \lambda_1 e^{-\lambda_1 t_1} dt_1 dt_4 \\ &= \int_{t_4=0}^{\infty} \left(1 - e^{-\lambda_1 t_4}\right) f_4(t_4) dt_4 \\ &= 1 - [f_2^*(\lambda_1)]^2 . \end{aligned} \quad (1)$$

In (1), if we assume that t_2 has the Gamma distribution (which is widely assumed in telecom modeling; see [6] and the references therein), then

$$\Pr[t_1 < t_4] = 1 - \left(\frac{1}{\lambda_1 \lambda_2 V_2 + 1}\right)^{\frac{2}{V_2 \lambda_2^2}} . \quad (2)$$

On the other hand, suppose that t_1 has an arbitrary distribution and that t_2 is exponentially distributed with the mean $1/\lambda_2$. Then, $t_4 = t_2 + t_3$ is an Erlang-2 random variable, and $\Pr[t_1 < t_2 + t_3]$ is derived as

$$\begin{aligned}\Pr[t_1 < t_4] &= \int_{t_1=0}^{\infty} f_1(t_1) \int_{t_4=t_1}^{\infty} \lambda_2^2 t_4 e^{-\lambda_2 t_4} dt_4 dt_1 \\ &= \int_{t_1=0}^{\infty} f_1(t_1)(e^{-\lambda_2 t_1} + \lambda_2 t_1 e^{-\lambda_2 t_1}) dt_1 \\ &= f_1^*(\lambda_2) - \lambda_2 \left[\left. \frac{df_1^*(s)}{ds} \right|_{s=\lambda_2} \right] . \end{aligned} \quad (3)$$

If t_1 has the Gamma distribution, (3) is rewritten as

$$\Pr[t_1 < t_4] = \left(\frac{1}{\lambda_1 \lambda_2 V_1 + 1}\right)^{\frac{1}{V_1 \lambda_1^2}} + \left(\frac{\lambda_2}{\lambda_1}\right) \left(\frac{1}{\lambda_1 \lambda_2 V_1 + 1}\right)^{\frac{1}{V_1 \lambda_1^2} + 1} . \quad (4)$$

Equations (2) and (4) are validated against the discrete event simulation experiments, which show that the discrepancies between the analytic and simulation results are within 0.3%.

Since t_2 (t_3) involves an international trunk, it is reasonable to assume that $2E[t_1] \le E[t_2] \le 5E[t_1]$. Fig. 2 plots $\Pr[t_1 < t_4]$ against $E[t_2]/E[t_1]$, V_1, and V_2. The figure indicates that the call setup in

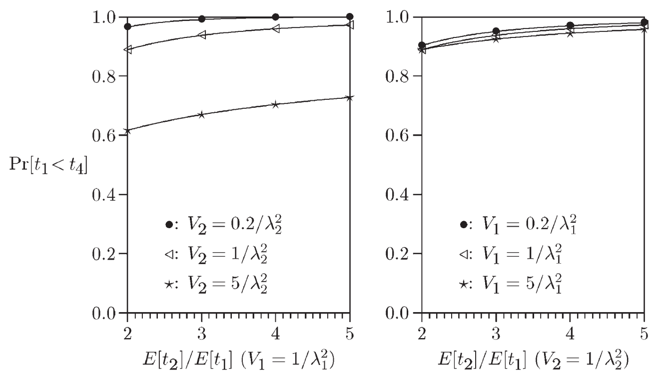

Fig. 2. Effects of λ_1/λ_2, V_1, and V_2 on $\Pr[t_1 < t_4]$.

the roaming group approach is much faster than that in the 3GPP approach. This figure also indicates that the variances of t_2 and t_3 have more impact on $\Pr[t_1 < t_4]$ than $E[t_2]/E[t_1]$ does. Therefore, to support this kind of routing services, reducing the variances of delays are essential.

Through the roaming software installed in the handsets, call setup is a transparent process where the call parties have the same call setup experience as before. The roaming gateway utilizes the short message protocol to download/update the mapping table in a handset. The table download operation is executed only when a new member is added to a roaming group. If the table size is too large to be included in one short message, the table is delivered via multiple short messages using the concatenated short message technique. The table update operation is executed only when the roamer moves to another country. In other words, the update frequency is typically very low, and our solution consumes little handset power (similar to the manipulation of address book in the handset). To enhance the security, the short message can be encrypted using the *Rivest–Shamir–Adleman* (RSA) or the identity-based schemes [7].

In the roaming group solution, existing telecom elements (e.g., HSS, MSC, and GMSC) and protocols (e.g., SS7 and short message protocol) are not modified. The telecom network is slightly modified by adding a plug-in roaming gateway (this plug-in's effort is very low). Therefore, the roaming group solution is an effective approach for reducing international call costs.

As a final remark, this solution is especially attractive for a group of travelers who roam to the same visited country and communicate with each other frequently during the trip.

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On Predicting Convergence of Iterative MIMO Detection-Decoding With Concatenated Codes

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***Abstract*—We evaluate the applicability of methods from stochastic decoding analysis to convergence prediction of iterative multiple-input–multiple-output (MIMO) detection decoding. The one-parametric conditional Gaussian log-likelihood ratio (LLR) distribution model, which underlies EXtrinsic Information Transfer (EXIT) charts, is not adequate for some practically relevant scenarios such as fading MIMO channels. A more recent two-parametric Gaussian model, which better fits arbitrary distributions, can be combined with an offset compensation to allow for a chart-based prediction of the convergence of iterative receiver processing in these cases.**

***Index Terms*—Convergence, EXtrinsic Information Transfer (EXIT) chart, iterative detection decoding, multiple-input multiple-output (MIMO), turbo code.**

I. Introduction

Iterative detection decoding for coded multiple-input multiple-output (MIMO) transmission is known to be capable of achieving near-capacity performance [1]. The usage of iterative processing naturally leads to the question of convergence.

EXtrinsic Information Transfer (EXIT) charts are widely used for predicting and illustrating convergence of iterative decoding of concatenated codes [2], [3]. The model underlying the chart assumes that the log-likelihood ratios (LLRs) of the transmit bit values are distributed after the symbol demapper according to binary phase-shift keying (BPSK) transmission over an additive white Gaussian noise (AWGN) channel, resulting in a one-parametric conditional Gaussian distribution (conditioned on the transmit bit value).

EXIT charts have also been used to model the convergence of iterative MIMO detection decoding. In [4], they are applied to optimize irregular repeat accumulate codes for MIMO transmission and iterative receiver processing. An optimization of turbo-coded space-time block code transmission based on EXIT charts is presented in [5]. Hou *et al.* [6] used EXIT charts to analyze and optimize MIMO transmission with low-density parity-check codes.

On the other hand, in [7], it is argued that, even if the input of a log-*a posteriori* probability (APP) decoder follows a one-parametric Gaussian distribution, the output needs to be described by two parameters (mean and variance) to adequately represent the dynamics of turbo decoding. This raises questions about the applicability of the stochastic decoding analysis methods, which we elaborate on in this paper.

The contribution of this paper is to combine [2], [3], and [7], together with a new offset compensation (to account for higher order distribution moments) into a chart-based prediction method, which we verify to yield acceptable prediction accuracy for different receiver computation schedules in iterative MIMO detection decoding with turbo codes.

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