Transactions Papers

Active Location Reporting for Emergency Call in UMTS IP Multimedia Subsystem

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***Abstract*—The *IP Multimedia Core Network Subsystem* (IMS) provides multimedia services for Universal Mobile Telecommunications System (UMTS). In IMS, an emergency call is established by an *Emergency-Call Session Control Function* (E-CSCF). The E-CSCF dispatches the call to the nearest *Public Safety Answering Point* (PSAP) according to the location of the caller. After emergency call setup, the caller's location is tracked by the PSAP through Location Polling. This paper investigates the performance of location tracking. Then we propose the Active Location Reporting scheme to improve the performance of location tracking. Our study indicates that the Active Location Reporting scheme may significantly outperform the Location Polling scheme.**

***Index Terms*—Emergency call, IP multimedia core network subsystem (IMS), location tracking, Universal Mobile Telecommunications System (UMTS).**

I. Introduction

UNIVERSAL Mobile Telecommunications System (UMTS) is one of the major standards for the third generation (3G) mobile telecommunications. In UMTS, the *IP Multimedia Core Network Subsystem* (IMS) provides multimedia services by utilizing the *Session Initiation Protocol* (SIP) [1], [2].

Figure 1 illustrates a simplified UMTS network architecture [1], [2], [3]. This architecture consists of a *Radio Access Network* (RAN; Figure 1 (a)), the *General Packet Radio Service* (GPRS) core network (Figure 1 (b)) and the IMS network (Figure 1 (c)). The *Home Subscriber Server* (HSS; Figure 1 (1)) is the master database containing all user-related subscription information. The *Serving GPRS Support Node* (SGSN; Figure 1 (2)) is responsible for packet delivery to and from *User Equipments* (UEs; Figure 1 (3)). The *Gateway Mobile Location Center* (GMLC; Figure 1 (4)) supports *Location Service* (LCS). The GPRS core network connects to the IMS network through *Gateway GPRS Support Nodes* (GGSNs; Figure 1 (5)). To establish a data session, a *Packet Data Protocol* (*PDP*) *Context* must be activated before a UE can access the IMS network. A *Public Safety Answering Point* (PSAP; Figure 1 (6)) dispatches emergency calls according to the types of emergent events (e.g., fire). When the UE originates an emergency call, the call is established by an *Emergency-Call Session Control Function* (E-CSCF; Figure 1 (7)), which dispatches the call to the nearest PSAP according to the location of the UE.

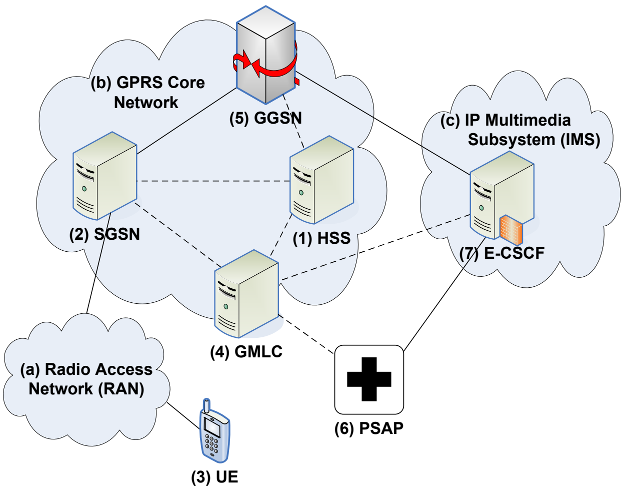

Fig. 1. The UMTS network architecture.

The LCS utilizes one or more positioning methods [4], [5] between the RAN and the UE to determine the location of a UE. Four positioning methods are specified in 3GPP TS 25.305 [4]. These methods are briefly described as follows:

The Cell-ID-based method determines the UE's position based on the coverage of Service Areas (SAs). An SA includes one or more cells (base stations). At most one-cell-sized accuracy (about 500 meters) can be achieved when the SA includes only one cell.

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The Observed Time Difference of Arrival (OTDOA) method utilizes trilateration to determine the UE's position. At least three concurrent downlink signals from different cells are measured in the UE. The time differences among the signal arrivals are calculated to form hyperbolic curves. The intersection of these curves is then used to indicate the UE's position. This method provides location accuracy within 50-150 meters.

The Assisted Global Positioning System (A-GPS) method speeds up GPS positioning by downloading GPS information through the RAN. Execution of A-GPS positioning only requires several seconds while execution of normal GPS positioning requires 30 seconds to several minutes. GPS modules are installed in both the UE and the RAN. This method provides location accuracy within 5-15 meters.

The Uplink Time Difference of Arrival (U-TDOA) method evolves from the OTDOA method. This method utilizes uplink signals instead of downlink signals. A normal uplink signal from the UE is measured in different cells, and no extra signal is required. Same calculation process as OTDOA is then conducted to find out the UE's position. Since the measurement and the calculation process are exercised only in the RAN, this method does not require any modification to the mobile phone. This method provides location accuracy within 50-150 meters.

Without loss of generality, we consider the Cell-ID-based method in this paper (the Cell-ID-based method supports all kinds of UEs, while other methods may require UEs to measure extra signal). The conclusions also apply to other positioning methods except that the accuracy of location measured in Cell-ID-based method is SA, while the accuracy measured in, for example, OTDOA is meter. This paper is organized as follows. Section II describes IMS emergency call setup and location tracking. Then we propose the Active Location Reporting scheme to improve the performance of location tracking. In Section III, we describe an analytic model to study the performance of location tracking. The proposed analytic model is validated against simulation experiments. Based on the simulation experiments, Section IV investigates the performance of location tracking.

II. Emergency Call Setup and Location Tracking

This section describes the IMS emergency call setup and location tracking procedures. We first elaborate on the call setup procedure and the Location Polling scheme proposed in 3GPP [6], [7]. Then we propose the Active Location Reporting scheme that improves the performance of location tracking.

A. Emergency Call Setup

Before the IMS emergency call is set up, the UE has attached to the network through the RAN. Figure 2 illustrates IMS emergency call setup message flow defined in 3GPP [6] with the following steps:

Step CS-1. The UE performs PDP context activation that establishes the IP connectivity to the IMS through the GPRS network [2].

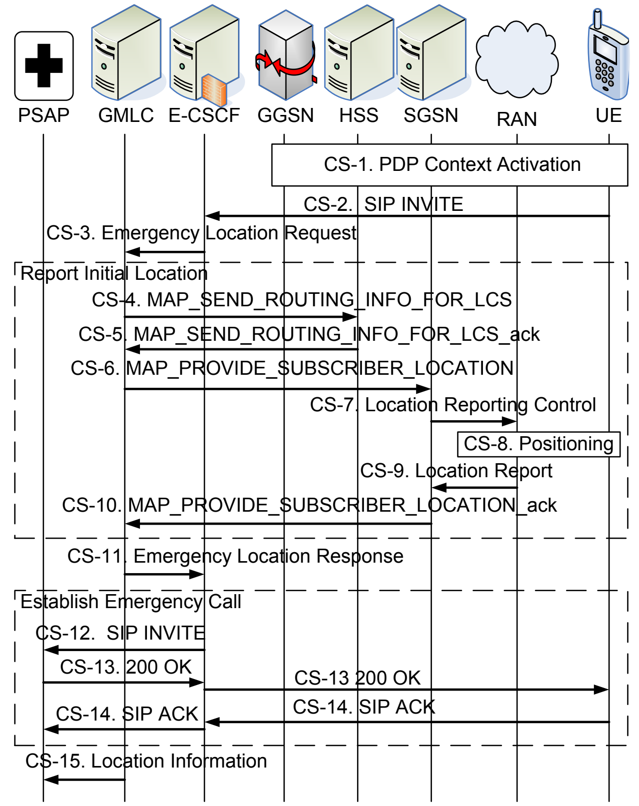

Fig. 2. IMS emergency call setup.

Step CS-2. The UE sends the SIP INVITE message to the E-CSCF. This message includes the supported positioning methods of the UE (i.e., Cell-ID-based in our example).

Step CS-3. The E-CSCF uses the received information to determine a GMLC and sends the Emergency Location Request message to the GMLC, which includes all UE-related information received at Step CS-2.

Steps CS-4 and 5. The GMLC exchanges the MAP_SEND_ROUTING_INFO_FOR_LCS and MAP_SEND_ROUTING_INFO_FOR_LCS_ack message pair with the HSS to obtain the SGSN address for the UE.

Step CS-6. The GMLC sends the MAP_PROVIDE_SUBSCRIBER_LOCATION message to the SGSN to request the UE's location. In this message, the locationEstimateType parameter is set to "initialLocation".

Step CS-7. Upon receipt of the MAP_PROVIDE_SUBSCRIBER_LOCATION message, the SGSN sends a Location Reporting Control message to the RAN to trigger the positioning procedure. In this message, the Request Type is set to "report directly".

Step CS-8. The RAN and the UE exercise the Cell-ID-based positioning procedure to obtain the location estimate information of the UE (i.e., the SA identity of the UE).

Step CS-9. The RAN returns the Location Report message with the SA identity to the SGSN.

Step CS-10. The SGSN returns the SA identity to the GMLC through the MAP_PROVIDE_SUBSCRIBER_LOCATION_ack message.

Step CS-11. The GMLC selects a suitable PSAP according to the SA of the UE and replies the Emergency Location

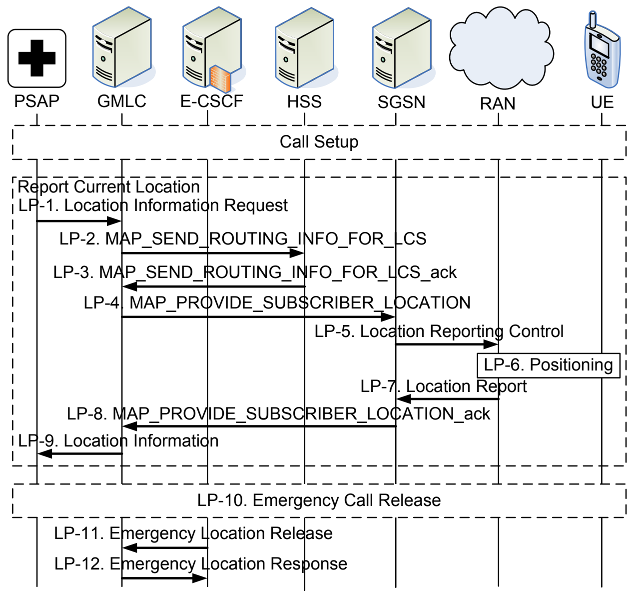

Fig. 3. Location polling.

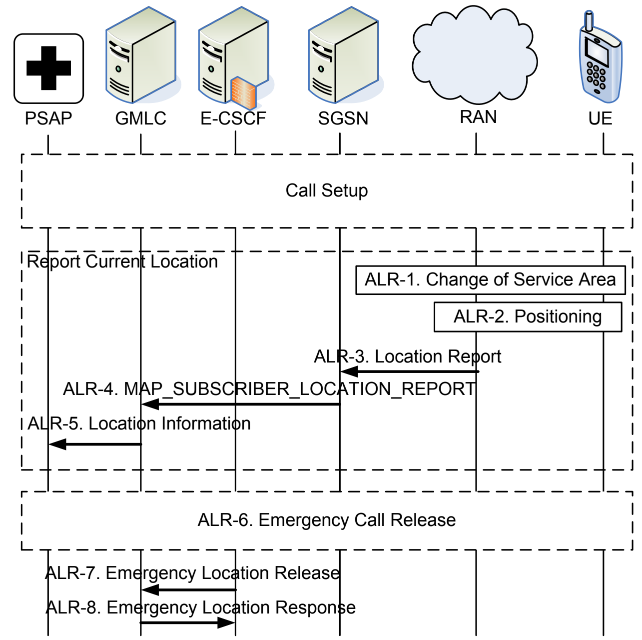

Fig. 4. Active location reporting.

Response message with the selected PSAP address to the E-CSCF.

Steps CS-12-14. The E-CSCF forwards the SIP INVITE to the PSAP. The PSAP and the UE exchange the 200 OK and the SIP ACK messages through the E-CSCF. After the PSAP has received the SIP ACK message, the emergency call is established.

Step CS-15. The GMLC sends the location information obtained at Step CS-10 to the PSAP after the call has been established.

B. Location Polling

A UE may move during an emergency call, and the PSAP may need to monitor the UE's location in real time. In 3GPP TS 23.271 [7], the UE's location is monitored through a polling procedure where the PSAP periodically queries the UE's location. In each polling query, the following steps are executed (see Figure 3).

Step LP-1. The PSAP sends the Location Information Request message to the GMLC.

Steps LP-2-8. These steps are similar to Steps CS-4-10 in Figure 2 except that the parameter locationEstimateType in the MAP_PROVIDE_SUBSCRIBER_LOCATION message is set to "currentLocation".

Step LP-9. The GMLC returns the SA identity of the UE to the PSAP.

Steps LP-10-12. When the emergency call is terminated, the E-CSCF exchanges the Emergency Location Release and Response message pair with the GMLC to terminate location tracking.

C. Active Location Reporting

In the Location Polling scheme, if the UE does not change its location between two queries, the second query is wasted. On the other hand, if the UE has moved to several new locations between two location queries, then the PSAP may lose track of the UE. To resolve this issue, we propose the Active Location Reporting scheme that reports the UE's location upon change of its SA. Our scheme introduces two new locationEstimateTypes "initiateActiveReport" (to trigger Active Location Reporting) and "terminateActiveReport" (to terminate Active Location Reporting) in the MAP_PROVIDE_SUBSCRIBER_LOCATION message, and one new LCS event type "ActiveReporting" (to indicate the Active Location Reporting event). At emergency call setup, the locationEstimateType is set to "initiateActiveReport" at Step CS-6, and the Request Type is set to "change of service area" at Step CS-7. Since the IP connectivity exists during the IMS emergency call, the UE is in the Cell-Connected state and is tracked by the RAN at the cell level [2]. Therefore, the RAN can detect the movement of the UE at the cell level and report the new SA identity to the SGSN. In this approach, the GMLC maintains a UE-PSAP mapping table, and the (UE, PSAP) pair is stored in the GMLC at Step CS-11. The GMLC does not need to query the HSS to obtain the SGSN address of the UE (therefore, Steps LP-2 and LP-3 are eliminated). The Active Location Reporting scheme is illustrated in Figure 4 with the following steps:

Step ALR-1. When the UE moves to a new SA, the RAN detects this movement at the cell tracking mode [2] and then triggers the positioning procedure.

Step ALR-2. After the positioning procedure is executed, the UE's SA identity is obtained.

Step ALR-3. The RAN sends the Location Report message with the SA identity of the UE to the SGSN.

Step ALR-4. The SGSN sends the MAP_SUBSCRIBER_LOCATION_REPORT message with the SA identity to the GMLC.

Step ALR-5. From the UE-PSAP mapping table, the GMLC retrieves the PSAP address of the UE stored at Step CS-

11 and then sends the updated location information to the PSAP.

When the emergency call is terminated, the following steps are executed.

Step ALR-6. When the IMS call is released, the UE moves from the Cell-Connected mode to the Idle mode, and the RAN no longer tracks the movement of the UE [2].

Step ALR-7. The E-CSCF sends the Emergency Location Release message to the GMLC to terminate location tracking.

Step ALR-8. The GMLC returns the Emergency Location Response message to the E-CSCF and then deletes the (UE, PSAP) mapping from the UE-PSAP table.

The major difference between Active Location Reporting and Location Polling is at Steps ALR-1 and ALR-2. Active Location Reporting is triggered when the RAN detects the movement of the UE (through the standard tracking procedure at the Cell-Connected mode). Note that the HSS query (see Steps LP-2 and LP-3 in Figure 3) is not required for the Active Location Reporting scheme because of the active reporting of the RAN. The GMLC needs to maintain the (UE, PSAP) mapping so that when a UE changes the SA, the GMLC can report the location update to the corresponding PSAP.

III. Analytic Modeling of Location Polling

This section proposes an analytic model to study the performance of location tracking. Let N be the number of queries between two SA crossings. Five output measures are considered.

- α: the probability of *mis-tracking* for an SA crossing. An SA crossing is mis-tracked if there is no query between this SA crossing and the next SA crossing, and therefore the system does not know that the user has moved to this SA. It is clear that $\alpha = Pr[N = 0]$.
- T_i: the expected *invalid* period. The invalid period is defined as the period between when an SA crossing occurs and when the next query arrives under the condition that $N \geq 1$. In this period, the system does not know that the user has moved (i.e., the location known by the system is obsolete and therefore is "invalid").
- V_i: the variance of the invalid periods
- β: the probability that *redundant* queries exist between two SA crossings (i.e., $\beta = Pr[N > 1]$). It is clear that redundant queries create extra network traffic without providing useful location information.
- $E[N|N > 1]$: the expected number of queries between two SA crossings under the condition that $N > 1$. In other words, $E[N|N > 1] - 1$ is the expected number of redundant queries.

The smaller the above output measure values, the better the performance of location tracking. It is clear that for the Active Location Reporting scheme, optimal performance is achieved for these output measures, that is, $\alpha = 0$, $T_i = 0$, $V_i = 0$, and $\beta = 0$. On the other hand, the above output measure values are not 0 for the Location Polling scheme. This section derives α, T_i, V_i, β, and $E[N|N > 1]$ for Location Polling. Then we investigate if Active Location Reporting (the optimal case) significantly outperforms Location Polling.

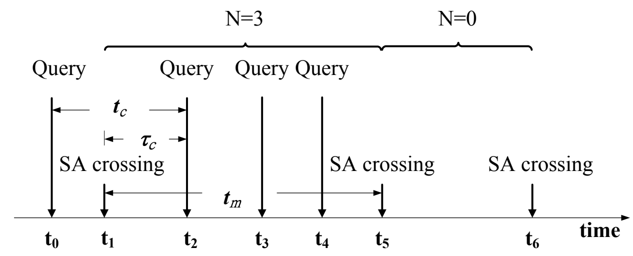

Fig. 5. Timing diagram for location polling.

Figure 5 illustrates the relationship between location queries and user movements. The UE changes its SA at t_1, t_5 and t_6, and the PSAP queries the UE's location at t_0, t_2, t_3 and t_4. In this example, $N = 3$ between t_1 and t_5, and $N = 0$ between t_5 and t_6. Let the SA residence time interval $t_m = t_5 - t_1$ be a random variable with the density function $f_m(\cdot)$ and the Laplace transform $f_m^*(\cdot)$. Let the inter-query interval $t_c = t_2 - t_0$ be a random variable with the exponential distribution with the mean $1/\lambda$ (i.e., the query stream forms a Poisson process). Then α is derived as

$$\alpha = Pr[N = 0] = \int_{t_m=0}^{\infty} e^{-\lambda t_m} f_m(t_m) dt_m = f_m^*(\lambda) \quad (1)$$

If t_m has Gamma distribution with the mean $1/\mu$ and the variance V_m, then (1) is re-written as

$$\alpha = \left(\frac{1}{V_m \mu \lambda + 1} \right)^{\frac{1}{V_m \mu^2}}$$

The Gamma distribution is selected because it has been shown that the distribution of any positive random variable can be approximated by a mixture of Gamma distributions (see Lemma 3.9 in [8]). Following the past experiences [9], [10], [11], we can obtain the SA residence time samples from the commercial mobile telecommunication operation and then use the statistical tools to fit the sample data by the Gamma distribution.

In Figure 5, $\tau_c = t_2 - t_1$ is the invalid period for the SA residence time interval $[t_1, t_5]$. In this period, the PSAP is not aware of the SA crossing at t_1. Since the query stream is a Poisson process, the density function $r_c(\cdot)$ for invalid period τ_c is the same as that for t_c because of the memoryless property of the exponential distribution. Consider the conditional density function $r_{c|N\geq 1}(\tau_c)$ where the PSAP issues more than one query in the SA residence time interval. From (1) and because $Pr[N \geq 1] = Pr[\tau_c \leq t_m]$, we have

$$r_{c|N\geq 1}(\tau_c) = \left[\frac{1}{1 - f_m^*(\lambda)} \right] \int_{t_m=\tau_c}^{\infty} r_c(\tau_c) f_m(t_m) dt_m \quad (2)$$

Based on (2) and the memoryless property of the exponential distribution, we derive the expected invalid period T_i as

$$\begin{aligned} T_i &= E[\tau_c | N \geq 1] \\ &= \int_{\tau_c=0}^{\infty} \tau_c r_{c|N\geq 1}(\tau_c) d\tau_c \\ &= \left[\frac{1}{1 - f_m^*(\lambda)} \right] \left[\left. \frac{df^*(s)}{ds} \right|_{s=\lambda} \right] + \frac{1}{\lambda} \end{aligned} \quad (3)$$

If t_m has a Gamma distribution, (3) is re-written as

$$T_i = \frac{1}{\lambda} - \frac{1}{\mu(V_m\mu\lambda+1)^{\frac{1}{V_m\mu^2}+1} - V_m\mu^2\lambda - \mu}$$

Similar to the derivation for T_i, we derive the variance V_i of the invalid periods as

$$\begin{aligned} V_i &= V[\tau_c|N\geq 1] \\ &= \frac{2(V_m\mu\lambda+1)^{\frac{1}{V_m\mu^2}}}{\lambda^2\left[(V_m\mu\lambda+1)^{\frac{1}{V_m\mu^2}}-1\right]} \\ &\quad -\frac{3V_m\lambda^2\mu^2+2\lambda\mu+\lambda^2+2\mu^2(V_m\mu\lambda+1)^2}{\lambda^2\mu^2(V_m\lambda\mu+1)^2\left[(V_m\mu\lambda+1)^{\frac{1}{V_m\mu^2}}-1\right]} \\ &\quad -\left[\frac{1}{\lambda}-\frac{1}{\mu(V_m\mu\lambda+1)^{\frac{1}{V_m\mu^2}+1}-V_m\mu^2\lambda-\mu}\right]^2 \end{aligned}$$

The probability β of redundant queries is derived as

$$\begin{aligned} \beta &= Pr[N>1] \\ &= 1-Pr[N=1]-Pr[N=0] \\ &= 1-\int_{t_m=0}^{\infty}\lambda t_m e^{-\lambda t_m} f_m(t_m)dt_m - \alpha \\ &= 1+\lambda\left[\left.\frac{df_m^*(s)}{ds}\right|_{s=\lambda}\right] - f_m^*(\lambda) \end{aligned} \quad (4)$$

If t_m has a Gamma distribution, (4) is re-written as

$$\beta = 1-\left(\frac{1}{V_m\lambda\mu+1}\right)^{\frac{1}{V_m\mu^2}}\left[1-\frac{\lambda}{\mu(V_m\lambda\mu+1)}\right]$$

Since the query stream is a Poisson process, N has Poisson distribution with mean λt_m. Therefore $E[N|N>1]$ is derived as

$$\begin{aligned} E[N|N>1] &= \sum_{n=2}^{\infty} n\left[\frac{\int_{t_m=0}^{\infty}\frac{(\lambda t_m)^n}{n!}e^{-\lambda t_m}f_m(t_m)dt_m}{\beta}\right] \\ &= \frac{\lambda}{\mu}+\frac{\lambda^2}{\mu}\times \\ &\quad \frac{V_m\mu^2+1}{\mu(V_m\mu\lambda+1)^{\frac{1}{V_m\mu^2}+1}-V_m\mu^2\lambda-\mu-\lambda} \end{aligned}$$

The above analytic model is validated against the discrete event simulation experiments. The discrete event simulation model is described in [12]. As shown in Table I (where $V_m = 1/\mu^2$), the analytic analysis is consistent with the simulation results.

TABLE I
COMPARISON OF ANALYTIC AND SIMULATION MODELS ($V_m = 1/\mu^2$)

λ	0.1μ	10μ
α (Analytic)	0.90909	0.090909
α (Simulation)	0.90914	0.090910
Error	0.0063 %	0.0013 %
T_i (Analytic)	$0.909/\mu$	$0.0909/\mu$
T_i (Simulation)	$0.907/\mu$	$0.0908/\mu$
Error	0.1374 %	0.1119 %
V_i (Analytic)	$0.8264/\mu^2$	$0.008265/\mu^2$
V_i (Simulation)	$0.8257/\mu^2$	$0.008271/\mu^2$
Error	0.0907 %	0.0804 %
β (Analytic)	0.00826	0.82645
β (Simulation)	0.00828	0.82657
Error	0.1875%	0.0153 %
$E[N\|N>1]$ (Analytic)	2.1	12
$E[N\|N>1]$ (Simulation)	2.103	11.99
Error	0.1794 %	0.0687 %

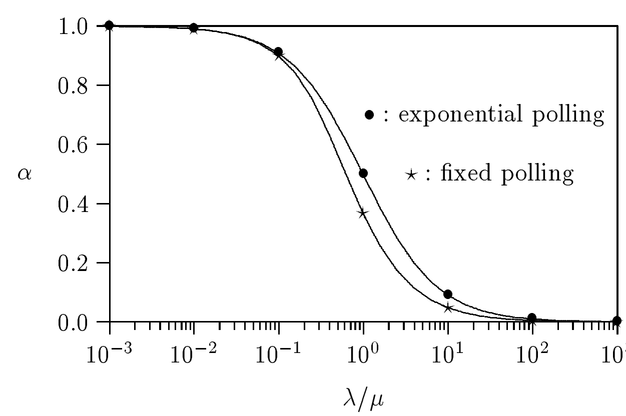

Fig. 6. Comparing fixed and exponential inter-query interval (Poisson SA crossing stream with the rate μ).

IV. NUMERICAL EXAMPLES

Based on the simulation experiments validated against the analytic model, this section investigates the performance of Location Polling. Two types of inter-query intervals can be considered. *Fixed* polling queries the UE's location with fixed period $1/\lambda$. On the other hand, in *exponential* polling, the inter-query interval has the exponential distribution with the mean $1/\lambda$. In this section, we first compare fixed polling with exponential polling. Our study will indicate that fixed polling outperforms exponential polling. Then we compare fixed polling with the Active Location Reporting scheme. We will show that Active Location Reporting scheme outperforms fixed polling.

Assume that the SA residence time interval t_m has the exponential distribution with the mean $1/\mu$ (i.e., the SA crossings form a Poisson process). From (1), the probability α for exponential polling is expressed as

$$\alpha = f_m^*(\lambda) = \frac{\mu}{\lambda+\mu} \quad (5)$$

Since the SA crossings form a Poisson process, the number X of SA crossings in an arbitrary fixed inter-query interval $1/\lambda$ has a Poisson distribution with the mean μ/λ. When $X>0$, there are $X-1$ SA residence time intervals without any query. Therefore, the probability α for fixed polling is expressed as

$$\alpha = \frac{E[X-1|X>0]}{E[X|X>0]} = 1-\frac{\lambda}{\mu}\left(1-e^{-\mu/\lambda}\right) \quad (6)$$

Figure 6 plots α for fixed and exponential polling approaches based on (5) and (6). The figure indicates that fixed polling outperforms exponential polling in terms of the α measure. For all cases considered, fixed polling outperforms exponential

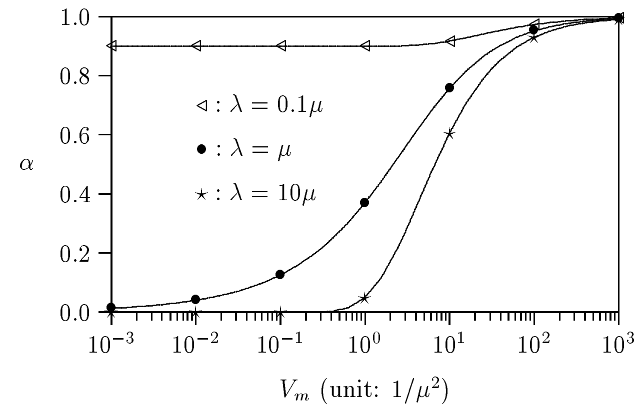

Fig. 7. Effects of λ and V_m on α.

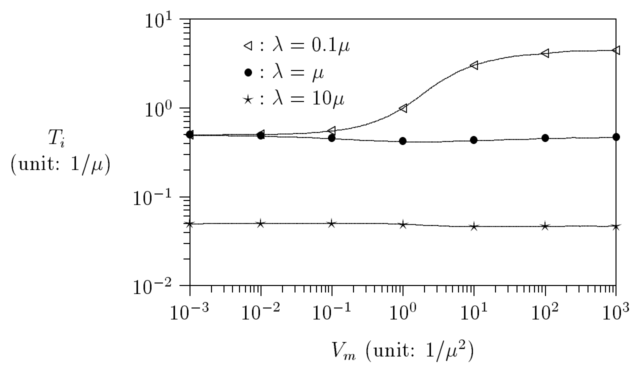

Fig. 8. Effects of λ and V_m on T_i.

polling when λ is large (e.g., $\lambda = 10\mu$), while both approaches have similar performance when λ is small. Detailed comparison between fixed polling and exponential polling will not be presented in this paper. Instead, this paper uses the analytic model based on exponential polling to validate against the simulation model. In the remainder of this paper, we only consider fixed polling through simulation experiments. General conclusions drawn from this paper also apply to exponential polling. The effects of the input parameters are investigated as follows.

Effects of λ and V_m on the mis-tracking probability α : Figure 7 plots α for Gamma SA residence time intervals with different variance values. The figure indicates that α increases as V_m increases. This phenomenon is explained as follows. When the SA residence time intervals become more irregular (i.e., V_m increases), we will observe more SA residence time intervals without any query. On the other hand, the number of SA residence time intervals with queries will not increase as V_m increases, but the number of queries in an SA residence time interval will increase. Therefore, larger α is observed. The figure also indicates that when V_m is very large, α is not sensitive to the λ values, and poor accuracy is always observed (i.e., α is large).

Effects of λ and V_m on the expected invalid period T_i : Figure 8 plots T_i against λ and V_m. When λ is small (e.g., $\lambda = 0.1\mu$), T_i increases as V_m increases. This phenomenon is explained as follows. As V_m increases, more long and short SA residence time intervals are observed. For short SA residence time intervals, it is likely that $N = 0$, and these intervals will not contribute to τ_c. In other words, when V_m increases, more long τ_c intervals are observed. Therefore, T_i increases as V_m increases. When λ is large (e.g., $\lambda = 10\mu$), T_i becomes less sensitive to V_m.

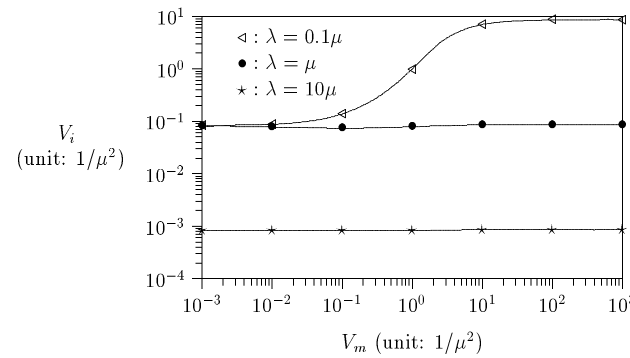

Fig. 9. Effects of λ and V_m on V_i.

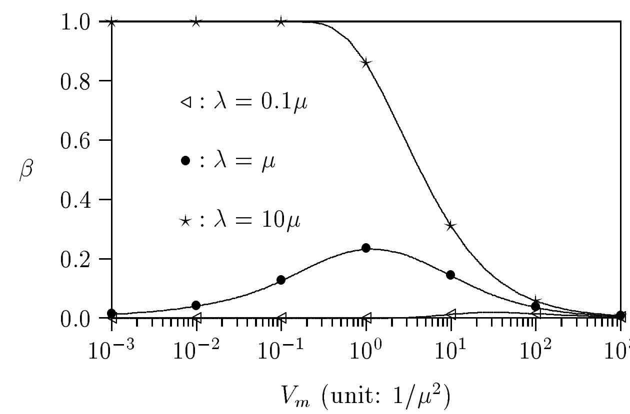

Fig. 10. Effects of λ and V_m on β.

Effects of λ and V_m on variance V_i of invalid period : Figure 9 plots V_i against λ and V_m. When λ is small (e.g., $\lambda = 0.1\mu$), V_i increases as V_m increases. When λ is large (e.g., $\lambda = 10\mu$), V_i becomes less sensitive to V_m. This phenomenon is similar to that for T_i.

Effects of λ and V_m on the probability β of redundant query Figure 10 plots β against λ and V_m. As V_m increases, two effects are observed: (I) More SA residence time intervals without any query are observed, which results in smaller β, (II) More SA residence time intervals with more than one query are observed, which results in larger β. When λ is large (e.g., $\lambda = 10\mu$), Effect (I) is more significant than Effect (II). Therefore, β is a decreasing function of V_m. For $\lambda = \mu$, β increases and then decreases as V_m increases. When V_m is small, Effect (II) is more significant, while Effect (I) is more significant when V_m is large. Therefore, β increases and then decreases as V_m increases. When λ is small (e.g., $\lambda = 0.1\mu$), both Effects (I) and (II) are insignificant.

Effects of λ and V_m on $E[N|N > 1]$: Figure 11 shows that $E[N|N > 1]$ is an increasing function of V_m. This phenomenon is explained as follows. As V_m increases, more long SA residence time intervals are observed. Since query events are more likely to fall on long SA

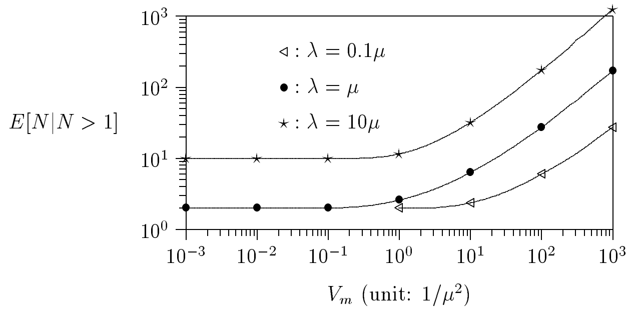

Fig. 11. Effects of λ and V_m on $E[N|N > 1]$.

residence time intervals, larger $E[N|N > 1]$ is observed. Therefore, $E[N|N > 1]$ increases as V_m increases. When V_m is small, (i.e., $V_m \le 1/\mu^2$), $E[N|N > 1]$ is not sensitive to the change of V_m.

V. Conclusions

This paper investigated emergency call mechanism for IMS. After an IMS emergency call is established, the caller's location is tracked by the PSAP through Location Polling. This paper proposed the Active Location Reporting scheme to improve the performance of location tracking. Our study indicated that the Active Location Reporting scheme significantly outperforms the Location Polling scheme. We observed the following results:

- When the query frequency is low (i.e., λ is small) and when the movement is irregular (i.e., when V_m is large), Active Location Reporting significantly outperforms Location Polling in terms of the α (mis-tracking probability) performance.
- When the query frequency is low, Active Location Reporting significantly outperforms Location Polling in terms of the T_i and V_i (for the invalid period) performance.
- When the query frequency is high and when the movement is regular, Active Location Reporting significantly outperforms Location Polling in terms of the β (redundant query probability) performance.

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