Mobile Location Estimation Based on Differences of Signal Attenuations for GSM Systems

Ding-Bing Lin, Member, IEEE, and Rong-Terng Juang, Student Member, IEEE

Abstract—The GSM system provides measurements regarding the signal attenuations from serving and neighboring base stations for managing radio resources. This paper proposes a mobile location estimation based on differences of downlink signal attenuations, which yield circles along which the mobile may lie. Then, the curves intersect at the estimated mobile position. The proposed method does not require a known and accurate path loss modeling, reduces the impact of shadowing on location, and is capable of being applied in existing systems without hardware development. Performance simulations include environments involving different standard deviation and cross-correlation of shadowings, and different abilities to detect base stations. Simulations demonstrate encouraging performance with only three base stations being available in severe shadowing environments. Additionally, the results of driving measurement show that the proposed method outperforms the Cell-ID method in a real GSM system in urban Taipei city.

Index Terms—Mobile location, signal attenuation differences.

I. INTRODUCTION

Mobile locations could support many applications, such as emergency services, roadside assistance, billing, navigation, tracking, and so on [1]-[3]. Over recent decades, numerous studies have examined the mobile location estimations, which can be divided into five categories. The first category is the GPS (Global Positioning System) [4], which provides accurate positioning based on satellite transmitted signals. However, the GPS may fail when satellite signals are blocked, for example in a setting when the mobile is used in indoors, in underground car parks, and in urban canyons. The GPS has been standardized in GSM (Global System for Mobile Communications) networks as the Assisted-GPS method [3],[5], which requires hardware development in both the mobile terminal and the network. The second category estimates the mobile location based on the Received Signal Strength Indication (RSSI) measurements [6]-[9]. This approach uses the relationship between the received signal strength and the distance from the base stations (BS) to the mobile station. Unfortunately, the accuracy of this approach may be inaccurate because of the complex propagation mechanisms. The third category locates the mobile via the angle-of-arrival (AOA) of a signal from the mobile at several BSs [10]-[12]. The AOA estimation can be used to draw a line of bearing (LOB) from the BS to the mobile; multiple LOBs intersect at the estimated mobile position. This technique requires no time synchronization between stations and can work with as few as two BSs. However, the AOA estimation requires a complex antenna system and may suffer from non-line-of-sight (NLOS) propagation, making it impractical for networks in urban environments.

The fourth category determines mobile location by measuring the time-of-arrival (TOA) [1]-[3],[5], which provides the estimate of the distance between the BS and the mobile since electromagnetic waves propagate at the speed of light. The estimated distance yields a circle, centered on the BS. The mobile location then can be determined at the intersection of circles using multiple TOAs. The simplest way for GSM systems to measure the TOA is by using timing advance (TA) [13]-[15], which measures run-trip time between the BS and the mobile. Multiple TAs can be obtained by forcing the mobile to make handover attempts from the serving BS to the neighboring BSs. However, the theoretical distance resolution of TA is 550m, which may be too large to enable accurate location estimation. Another positioning technique based on propagation delay time, namely TDOA (Time Difference of Arrival), calculates the differences in TOAs of a mobile signal at multiple pairs of BSs [1]-[3],[5],[16],[17]. Each TDOA measurement yields a hyperbolic curve along which the mobile may lie. The mobile position can be determined at the intersection of these curves. Two TDOA techniques are standardized in GSM networks as UL-TOA (Uplink TOA) and E-OTD (Enhanced Observed Time Difference) [18]-[24]. Nevertheless, potential disadvantages of the propagation-time-based techniques are NLOS propagation and the need for timing synchronization between stations.

The final category recognizes the channel status, such as path loss and power delay profile, for mobile location estimations [25],[26]. The mobile position is identified by matching the actual signatures of the received signal with the entries stored in a database available at the network. The location accuracy by using the channel status recognition
depends strongly on channel status variations and the database size. However, the construction and updating of the large database is time-consuming. This “fingerprint” technique is attracting increasing attentions for indoor applications, for which database management is easier than in wide outdoor areas.

The GSM system provides measurement reports about the signal attenuations from serving and neighboring BSs for managing radio resources. This paper proposes a mobile location estimation method based on the differences between downlink signal attenuations for GSM systems. This method does not require a known and accurate path loss modeling, reduces the impact of shadowing on location, and is able to provide location services to users with current handsets which lack location functionality.

The rest of this paper is organized as follows. Section II presents a detailed description of the proposed method. Section III discusses the location error. Subsequently, Section IV explores the location performance in different shadowing environments with different abilities to detect BSs. Next, Section V examines the performance in a real GSM system in urban Taipei City. Finally, Section VI presents some concluding remarks.

II. THE PROPOSED MOBILE LOCATION ESTIMATION METHOD

In a real propagation environment, path loss and shadowing (fast fading is ignored because it can be averaged out) attenuate the signal power. Path loss, including all of the possible loss elements associated with interactions between the propagating wave and any objects between the transmitting and receiving antennae, basically increases with the signal travel distance. Numerous models have been proposed over the past decades. The Hata model, Lee model and Walfisch-Ikegami model [27] are some of the notable examples, which are frequently used in wireless communication systems. Shadowing results from differences in levels of clutter (buildings, trees, etc.) along the path traveled by the wave, causing signal variations with respect to the nominal value given by path loss models. Shadowing is generally assumed to be a lognormal distributed random variable, a zero-mean Gaussian random variable when expressed in decibels [27].

Based on the Cost231 Hata model, a generalized form for signal attenuation, $A$, between a BS and a mobile, separated by $d$ in a large city, can be modeled as

$$A_{dB} = k_1 + k_2 \log_{10} f + k_3 \log_{10} h_b + 10n \log_{10} d$$
$$+ k_5 \left(\log_{10}(k, h_m)\right)^2 + X,$$  \hspace{1cm} (1)

where $n = (k_6 + k_7 \log_{10} h_b)/10$ represents the path loss exponent ranging from two to four, $k_1, k_2, k_3, k_5, k_6, k_7$ denote different constants in the same clutter type of environment, $f$ is the carrier frequency, $h_b$ and $h_m$ are, respectively, the heights of BS and mobile, and $X$ is a zero-mean Gaussian random variable with variance $\sigma^2$. Figure 1 sketches a scenario in which one mobile simultaneously connects with two BSs, $BS_1$ and $BS_2$. Assume that 1) these two links operate at an identical frequency band, 2) both BSs have the same height, and 3) these two links are in the same type of clutter environment so that parameter sets, $\{k_1, k_2, k_3, n, k_5, k_7\}$, for these two paths are the same.

![Fig. 1. Sketch of location scenario.](image)

Denoting $A_1$ and $A_2$ as the signal attenuations of the two paths, respectively, the difference between $A_1$ and $A_2$ has the form,

$$A_1 - A_2 = 10n \log_{10}(d_1/d_2) + (X_1 - X_2)$$ \hspace{1cm} (2)

where $d_1$ and $d_2$ are the distances between the mobile and the BSs for $BS_1$ and $BS_2$, respectively, and $X_1$ and $X_2$ represent the shadow components of the two paths. The correlation between $X_1$ and $X_2$ is termed “site-to-site correlation” [27], which primarily depends on 1) the angle, $\phi$, between the two paths along the mobile to BSs and 2) the relative values of the two path lengths, $d_1$ and $d_2$. Denoting the variances of $X_1$ and $X_2$ and the correlation coefficient between $X_1$ and $X_2$ as $\sigma^2$ and $\rho$, respectively, then $X' = X_1 - X_2$ is a zero-mean Gaussian random variable with variance $2\sigma^2(1-\rho)$. The ratio of $d_1$ to $d_2$, symbolized by $k$, can be derived from (2),

$$k = d_1/d_2 = 10^{(A_1 - A_2)/10n}$$ \hspace{1cm} (3)

where the error term, $X'' = X'/\sqrt{2\sigma^2(1-\rho)}$, is a zero-mean Gaussian random variable with variance $2\sigma^2(1-\rho)/(10n)^2$. Generally, the standard deviation of shadowings is greatest in suburban areas and smallest in open areas, and tendency to increase with increasing frequency and path length. Xia et al. found that the standard deviation ranges from 4.2dB to 7.7dB in suburban/residential environments and from 2.2dB to 8.3dB in urban environments for microcells operating in 900MHz frequency band [28]. Moreover, Saunders found that $\rho$ ranges from 0.3 to 0.8 when $d_1$ is 1Km and $d_2$ is 2Km [27]. Figure 2 exhibits the variance of $X''$ in different shadowing environments. In the case with 8dB shadowing, the variance of $X''$ is around 0.09 if the fading components are uncorrelated, and the variance reduces to 0.02 when the correlation increases to 0.8. Consequently, a small variation of
$X^*$ is expected in situations with high site-to-site correlation even in severe shadowing environments. That is, $k$ can be precisely estimated since $X^*$ has small variation in most environments. From (3), $k$ can be extracted without requiring knowledge of path loss modeling because it is related only to the difference in signal attenuations, the path loss exponent, and $X^*$.

Fig. 2. Variance of $X^*$ due to different shadowings.

Assume all the points are lying on the same plane in a Cartesian coordinate, $k$ yields a circle along which the mobile may lie,

$$
\left( x - \frac{k^2 x_2 - x_1}{k^2 - 1} \right)^2 + \left( y - \frac{k^2 y_2 - y_1}{k^2 - 1} \right)^2 = \left( \frac{1}{k^2 - 1} \right) + \frac{1}{k^2 - 1} \cdot D^2,
$$

where $(x_1, y_1)$ and $(x_2, y_2)$ are, respectively, the coordinates of BS$_1$ and BS$_2$, separated by $D$. Figure 3 illustrates the candidates of the mobile location, the circle intersections. The midpoint of the shortest distance between two circles is regarded as the intersection if the circles do not overlap, as illustrated in Fig. 3 (b) and (c). Because a maximum of seven BSs (one serving BS plus six neighboring BSs) are available in GSM systems, the maximum number of circles is $21$ ($7^2 C_2$), resulting in $420$ ($21^2 C_2$) intersections. Determining the mobile location at the mean of the intersections would be the simplest way but has lower accuracy. Caffery proposed a geometrical approach, which reduces two circular LOPs (line of position) to a straight LOP, and solves the LOPs using the least square method [29]. This paper determines the mobile position at the centroid of intersections, which is a heuristic way and similar to the Path-Gain Weighted Centroid in [30]. Because any particular intersection distance from other intersections is relative minor reliable in calculating mobile location, the mass of the $i$-th intersection is defined as

$$
m_i = \frac{1}{N} \sum_{j=1}^{N} \text{dist}(p_i, p_j), \quad j \neq i,
$$

where $N$ denotes the number of intersections, $p_i$ represents the coordinates of the $i$-th intersection, and $\text{dist}(p_i, p_j)$ is the geometric distance between positions $p_i$ and $p_j$. The centroid of the $N$ intersections then can be expressed as

$$
\bar{p} = \left( \frac{\sum_{i=1}^{N} m_i p_i}{\sum_{i=1}^{N} m_i} \right).
$$

Because one of the two intersections derived from two circles is located at relative large distance from the mobile position, half the intersections further from the centroid of the $N$ intersections are eliminated, and the centroid of the remaining $N/2$ intersections is regarded as the estimated mobile location.

Note: Although $k$ is defined as the ratio of $d_1$ to $d_2$, the circle comprising those points subject to $d_1 : d_2 = k$ is exactly the same as that comprising those points subject to $d_1 : d_2 = k^*$.

Fig. 3. Illustration of three intersection scenarios.

III. DISTANCE RATIOS AND CIRCLE ESTIMATION WITH ERRORS

This section discusses the errors of $k$ evaluation and circle determination owing to shadowings, cell radiuses, and propagation environments. The mean absolute error of the $k$ evaluation is defined as the average of absolute errors, $e_k$,

$$
e_k = \left| \frac{1}{A - A_i} - 10 \frac{\text{dB}}{10} \right|.
$$

By simulation, Fig. 4 shows the evaluation errors of $k$ and circle. Figures 4 (a) and (b), where the values of $(A_i - A)$ are set as 20dB and 40dB, respectively, indicate that the mean absolute error of $k$ evaluation increases with variance of $X^*$ and the value of $(A_i - A)$, but decreases with path loss exponent. Figures 4 (c) and (d) illustrate the circle determination error in a uniform cell planning with a cell
radius of 200m. The error of circle center, \((x_e, y_e)\), is defined as the geometric distance between the circle centers evaluated perfectly and with error, and the error of radius is defined as the absolute length difference between the radiuses obtained using the same principle. The figures display that the circle error increases with the variance of \(X^2\) and the path loss exponent, but decreases with the value of \((A_1 - A_2)\). These characteristics can be explained by investigating the slopes of the circular curves comprised of the centers and radiuses in different cases of \(k\), as shown in Fig. 5. The absolute value of the slopes approach infinity as \(k\) approaches to unity, and approach a constant as \(k\) approaches infinity or zero. That is, the immunity to error of the circle estimation strengthens as \(k\) approaches zero or infinity. Two factors support \(k\) approaching zero or infinity: 1) a cell planning with larger cell radiuses, which provide larger values of \((A_1 - A_2)\) with higher probability and 2) a smaller path loss exponent. Accordingly, the proposed location estimation is expected to display improved immunity to errors in rural macrocell environments compared to urban microcell environments.

### IV. LOCATION ESTIMATION SIMULATION

A software package, SignalPro\textsuperscript{®} by EDX Engineering, Inc., including a set of planning tools for wireless communication systems, was used to facilitate the simulation. Figure 6 is the simulation environment with 47 BSs. The mean and standard deviation of the BS heights are 36.9m and 5.6m, respectively. The Cost231-Hata model was applied for the path loss simulations. The actual mobile coordinates and their received power levels from a serving BS and six neighboring BSs at each position were also recorded. In the location estimation, the path loss exponent was set to 3.46 \((449-65.5\log_{10} h)/10\), where \(h = 36.9\) according to the Cost231-Hata model. To investigate the shadowing impact on accuracy of location estimation, two correlated zero-mean Gaussian random variables were assumed for shadowing simulations. The performance of the proposed method is assessed in terms of the location error, defined as the geometric difference between the actual and estimated mobile positions.

Figure 7 illustrates the location performance with different shadowings and seven BSs per estimate. The abscissa is the shadowing standard deviations, and the ordinate is the location errors, which indicates the performance of 67% of the estimates. The curves with different styles are performances with different shadowing correlation coefficients. In 8dB shadowing environment, the location errors are below 72.2m even if the shadowings are uncorrelated. When the shadowings are closely correlated (correlation coefficient of 0.8) the location errors reduce to 46.3m. Unlike the OTDOA-PE (Observed Time Difference of Arrival-Positioning Element) Positioning Method [31], which improves the ability to detect BSs using several positioning elements (PE) in known positions but not co-located with BSs, in UTRAN...
networks, the impact of the ability to detect BSs on location estimation should be explored. Figures 8 and 9 show the performances of the proposed method with different abilities to detect BSs. When only three BSs are available in severe shadowing environment, the location errors are below 95.6m with the shadowing correlation of 0.4, and rise to 107.1m with uncorrelated shadowings.

Additionally, the proposed method is compared with the Cell-ID method, the TDOA method, and the proposed method combined with the straight LOP approach described in Section II. The Cell-ID method, the simplest mobile location estimate in cellular communication systems, assumes the mobile location to be the same as that of the serving BS. In GSM systems, TDOA is derived from the difference between OTD (Observed Time Difference) and RTD (Real Time Difference) quantities [32],[33]. Spirito et al. modeled the measurement errors of TDOA in GSM systems as reaching values of \( \pm 2T_b \) \( (T_b = 3.69 \mu s) \) is GSM bit duration, which corresponds to 1100m [17]. Silventoinen et al. presented the distance measurement error in GSM systems as being around 513m in mean value and 436.0m in standard deviation [34],[35]. Spirito et al. found the error to be about 750m in mean value and 500m in standard deviation in urban environments [36]. The TDOA measurements yield a set of hyperbolas focused on BS coordinates. The easiest method of solving the equations is the least-squares estimation of the equations linearized by using Taylor-series expansion [37],[38], which requires an initial guess of the mobile position. Traditionally, the serving BS position serves as the initial guess, but it generally does not support good performance. In this work, the initial guess is set as the center of the polygon formed by the BSs connecting to the mobile [39]; the network is assumed to be synchronized between BSs (RTD=0) [21]; and the OTD estimation error is uniform distributed random variable over \( \pm 1.5T_b \) [17].

The third method, the combination of the proposed method and the straight LOP approach, refers to reducing the proposed circular LOSs to straight LOPs and solving them using the least square method. Table I summarizes the statistics of the location estimation simulations. The cell layout in the urban case is the same as in previous simulations, and the cell layout in suburban case is similar to that in urban case except that the average cell radius is about 1Km. The path loss exponent is set to 3.46 and 2.7, respectively, in urban and suburban cases. To carefully verify the performance of the proposed method in fading environments, the standard deviation and correlation coefficient of shadowings are respectively set to 8dB and 0.4 in the simulations involving seven BSs per estimate. The results show that the TDOA method is inadequate for mobile location in a GSM microcell network. Using the Cell-ID method and the proposed method combined with the straight LOP approach, the 67% of the location errors are below 149.8m and 79.6m, respectively. Using the proposed method, the error is 63.1m, representing 57.9% improvement compared to the Cell-ID method. In a suburban case, the proposed method achieves improvements of 65.1% over the Cell-ID method and 62.5% over the TDOA method.
The proposed location estimation was applied to a real GSM system (1800MHz) in urban Taipei city. The measurement reports include the Received Signal Levels (RXLEV) of the serving BS and stronger neighboring BSs. The RXLEV of the serving BS is measured on the traffic channel, which is power controlled. The RXLEV of neighboring BSs is measured based on their BCCH (Broadcast Control Channel), which is transmitted with a constant power. The RXLEVs are reported with a period of 0.48s from the mobile. The measurement equipment “TEMS™ Investigation GSM” provided by Ericsson was used for measurements along three selected routes. Calls were performed from a car, driving along the routes shown in Fig. 10. The mean and standard deviation of the building heights are 20.3m and 14.4m, respectively. The mean and standard deviation of BS heights are 26.4m and 10.2m, respectively. The measurement recorded the GPS coordinates of the mobile and the RXLEVs from BSs. The signal attenuations of these links were calculated according to the link budget.

<table>
<thead>
<tr>
<th>TABLE I STATISTICS OF LOCATION ESTIMATION ERRORS IN DIFFERENT ENVIRONMENTS.</th>
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</thead>
<tbody>
<tr>
<td><strong>LOCATION ERROR (METER)</strong></td>
</tr>
<tr>
<td>****                                               <strong>Urban Standing Environment</strong> <strong>Suburban Standing Environment</strong></td>
</tr>
<tr>
<td><strong>mean</strong></td>
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<tr>
<td><strong>std</strong></td>
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<td><strong>median</strong></td>
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<tr>
<td><strong>67%</strong></td>
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<td><strong>95%</strong></td>
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<td><strong>mean</strong></td>
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<tr>
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<td><strong>67%</strong></td>
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<tr>
<td><strong>95%</strong></td>
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</table>

Rows 67 percent and 95 percent denote the 67th and 95th percentile, respectively.

In the estimations, the path loss exponent is set to 3.56 according to the Cost231-Hata model. Table II summarizes the location error statistics (the location performance of TDOA method is not included here because our GSM network does not support TDOA estimation). Using the Cell-ID method, the 67% of the location errors are 194.1m, 274.7m, and 256.4m for routes 1, 2, and 3, respectively. Using the proposed method, the corresponding values are 145.1m, 192.2m, and 143.7m, respectively. The improvements of the proposed method compared to the Cell-ID method are 25.24%, 30.03%, and 43.95%, respectively. Figure 11 shows the accumulative distribution function (CDF) of the location errors along route 1. Again, the proposed method outperforms the Cell-ID method.

To further improve the proposed method, the error sources of the estimation should be discussed. The errors are as follows.

1) The determination of the path loss exponent.

Thought the BS heights vary in practical systems, the average height is used to determine the path loss exponent according to the Cost231-Hata model. Besides Cost231-Hata model, the system operator could determine more suitable values for path loss exponents in different environments through path loss modeling.

2) The assumption of BSs with equal heights.

Additional estimation errors are caused by the assumption of equal BS heights in the proposed method.

3) The influence of the antenna pattern in calculating signal attenuations.

The BS use directional antennae rather than the omnidirectional antennae in most practical systems. The antenna gain varies with the impinging angles, making it difficult to calculate the correct signal attenuation before obtaining knowledge regarding the mobile position. However, this could be solved by performing the estimation twice, with the first estimate being used for calculating antenna gain and then helping the second estimate.

![Fig. 10. Measurement environment, which covers an area of 2.1 by 1.6 Km². The triangles denote sector cells. Three routes are tested, route 1:A→B, route 2:C→D, route 3:E→F.](image)

VI. DISCUSSIONS AND CONCLUSIONS

This paper has proposed a mobile location method based on the differences in signal attenuations for GSM systems. The advantages of the proposed method include no need for a perfect path loss modeling, the reduction in shadowing impact on location, low computational complexity, and being applied in existing systems without hardware development. The estimation errors are contributed from 1) the determination of

...
path loss exponent, 2) the assumption of BSs with equal height, and 3) the influence of antenna patterns. Simulation demonstrated that the proposed method performs well even in severe shadowing environments. Moreover, the 67% of the location errors are adequate with three BSs per estimate. Additionally, the results of driving measurement show that the proposed method outperforms the Cell-ID method in a real GSM system in urban Taipei city.

Although the proposed method is designed for GSM systems, it can be applied to UTRAN networks with little modification by replacing RXLEV in the GSM system as RSCP (Received Signal Code Power) measurements, and the ability to detect BSs could be improved using a similar principle to OTDOA-PE. Finally, the proposed method and the TDOA method can be used as a hybrid location technique. Not only can the proposed method be combined with the TDOA method to yield more straight LOPs, but the proposed method can also be used as the initial guess in the TDOA method. This issue is left to be pursued by future studies.

### ACKNOWLEDGMENT

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### REFERENCES


### TABLE II

STATISTICS OF LOCATION ESTIMATION ERRORS IN A REAL SYSTEM (METER)

<table>
<thead>
<tr>
<th>Measurement Routes</th>
<th>Route 1 (1246 estimates)</th>
<th>Route 2 (1658 estimates)</th>
<th>Route 3 (2081 estimates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell-ID Method</td>
<td>170.6 222.8 219.3</td>
<td>194.1 274.7 256.4</td>
<td>194.1 274.7 256.4</td>
</tr>
<tr>
<td>Proposed Method</td>
<td>170.6 222.8 219.3</td>
<td>194.1 274.7 256.4</td>
<td>194.1 274.7 256.4</td>
</tr>
<tr>
<td>Avg. BS Number</td>
<td>6.2 5.9 6.0</td>
<td>6.2 5.9 6.0</td>
<td>6.2 5.9 6.0</td>
</tr>
<tr>
<td>Improvement over</td>
<td></td>
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<tr>
<td>Cell-ID Method at</td>
<td>25.24%</td>
<td>30.03%</td>
<td>43.95%</td>
</tr>
<tr>
<td>the 67th percentile</td>
<td></td>
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</tbody>
</table>

Rows 67 percent and 95 percent denote the 67th and 95th percentile, respectively.

Fig. 11. CDF of location estimation errors along route 1.


[32] ETSI TC-SMG, European digital telecommunications system (Phase 2); Radio subsystem synchronization (GSM 05.10), *ETSI-European Telecommunications Standards Institute*, May 1996.

[33] ETSI TC-SMG, European digital telecommunications system (Phase 2); Mobile radio interface layer 3 specification (GSM 07.08), *ETSI-European Telecommunications Standards Institute*, Aug. 1997.


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