Coverage of Hybrid Terrestrial-Satellite Location in Mobile Communications

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Abstract: **This work studies the improvement in service coverage obtained by three different ways of hybridising (terrestrial and satellite) triangulation location methods for cellular networks. Though the authors assume that terrestrial cellular networks use Enhanced Observed Time Difference (E-OTD) in 2G or Observed Time Difference Of Arrival (OTDOA) in 3G, and that the satellite GNSS uses Assisted Global Positioning System (A-GPS), their analysis can easily be generalized to address any other triangulation method. A simple analytical model is presented, which is used for evaluating the service coverage of each approach. The numerical results show how hybridisation leads to a high improvement and an easy balance between traffic and geographical coverage.**

1. Introduction

In the last decade we witnessed the growth of public mobile telephony at rates much higher than forecasted. Nevertheless, after this phase, many experts foresee that conventional (i.e. voice and data) services may reach saturation soon. Given this situation, operators are looking for new services. Providing a wide range of applications that inject data traffic into the network is seen as a promising approach [1].

In this new scenario, location is a key service. It is offered as a standalone service and at the same time serves as a lower layer for other services and applications (e.g. the user does not need to know his position, but the service he requested needs the position in order to be provided). In addition, the key role of location services (LCS) for public safety and emergency purposes leads regulators to enhance the requirements for quality. Location is also useful to operators beyond simply what revenue they can get from providing it; this is due to the possibility of using location information to optimise the management of network resources [2, 3].

1.1. The need for hybridisation

The necessary accuracy obtained from LCS can vary from several to hundreds of meters. Several technologies are currently available that provide different levels of accuracy and availability [4, 5, 6, 7]. Methods based on received power [8] such as Network Measurement Reports (NMR) have a poor accuracy due to the high variability of the radio path, fading, etc. Cell-ID is always available in cellular networks but the accuracy is poor since the cell radius can be long for certain scenarios. Timing Advance (TA) and Round Trip Time (RTT) are easy to use in GSM/GPRS and UMTS respectively, but they suffer from variable receiver chain delays in the MS and the precision of the TA is not very good.

This paper studies the hybridisation of triangulation methods that in general provide a better accuracy than non-triangulation ones. However, the latter also have less coverage: note that Cell-ID, TA/RTT and NMR are always available as long as the MS is connected to the cellular network, while there is no guarantee that three or more Base Stations (BS) or satellites will be within sight of the Mobile Station (MS) in order to triangulate at the specific moment that a location request is launched.

Terrestrial BS triangulation methods such as E-OTD for GSM/GPRS and OTDOA for UMTS work in a similar manner: 2D location is possible if three or more BSs are in sight. This is almost guaranteed in densely populated areas but seldom occurs in rural coverage, as the distances between BSs are typically long. A-GPS is similar to GPS but it relies on the cellular network to send assistance information to the MS (e.g. almanacs, etc). This assistance information greatly improves the time to track to satellites and hence the battery consumption. The performance of A-GPS is excellent in the open field, but poor indoors, in urban canyons, narrow streets and near to tall buildings; in all these scenarios the view of the necessary number of satellites is not guaranteed. This suggests that combining both techniques should have the consequence of improving coverage: only rural indoor situations should show location problems [9].

1.2. Goals

The aim of this paper is to compute the coverage of hybrid Terrestrial/Satellite location methods. The hybridisation is assumed to be carried out at the MS (i.e., is handset based): the MS computes its position with the available information from E-OTD/OTDOA and/or A-GPS. However, the main conclusions of this work do not change for other approaches. No further hybridisation is considered in this work: although some of the methods mentioned above could be added for hybridisation, their accuracy is poor when compared with that of triangulation methods. However, the procedure described can be easily generalized to encompass the hybridisation of more than two techniques.

2. Assumptions and notation

In this paper, coverage (*C*) is defined as the probability of a location technique or a combination of techniques being radio-accessible to network resources and terminal at a certain location request (i.e. traffic coverage) or place (i.e. territory coverage). In order to make a mathematical analysis feasible, the definition of coverage in this work is slightly different from the 3GPP definition of coverage [10]. Firstly, this study evaluates the probability of the MS being radio-covered by the service while 3GPP also takes into account possible unavailability caused by other constraints (e.g. network resources, signalling, etc.). Secondly, 3GPP considers only geographic coverage while this study extends the concept to traffic coverage. Consequently, there are two figures to be measured that are related to coverage:

- Traffic coverage (*CT*): Proportion of location requests correctly answered.
- Geographic coverage (*CG*): Proportion of the territory covered by the service.

In all cases, as it is assumed that the MS is within the coverage range of a network operator, so that the signal from at least one BS is always received. As both E-OTD/OTDOA and A-GPS need cellular coverage to be provided (i.e. both receive assistance through the cellular network), it makes no sense to compute the service coverage outside the coverage range of the cellular network. Note that 100% geographical coverage means that a location technique can be provided in all the territory covered by the cellular network, assuming that both the network and the terminal are available and have sufficient resources.

We define six environments: urban/suburban/rural, each of which is paired with indoor/outdoor. This classification is sufficiently precise to illustrate the procedure and thus achieve the numerical results in Section 4.

For a specific environment (*i*), users and the traffic they generate are assumed to be uniformly spread along the territory. It is assumed that if a user is covered by the location service (i.e. there is enough location information from BSs and/or satellites) his or her position can be correctly computed (i.e. error-free assumption). Hence

$$C^i = CT^i = CG^i \,, \qquad (1)$$

where the index *i* indicates the specific environment (e.g. urban indoor, etc). For the whole network, the uniformity assumption is far from being realistic: traffic and geographical coverage figures are related by the geographical distribution of traffic in different environments, as follows:

$$CT_{network} = \sum_{\forall i} t_i C^i ; \quad CG_{network} = \sum_{\forall i} g_i C^i \,, \qquad (2)$$

where t_i and g_i stand for the traffic and area shares of environment *i* respectively.

The number of BSs from which the MS is able to receive the signal is N_{BS}, while the number of satellites from which a valid pseudo-range is received is N_{SAT}. The probability density function (PDF) of receiving the signal from a specific number of BSs is known for each environment. The same can be said for the probability of seeing a specific number of GPS satellites. In all cases, the lowest level of accuracy of A-GPS and E-OTD is assumed to be enough to provide the MS location. For simplicity, only the case of 2D positioning is studied in this paper. Nevertheless, the proposed approach could be easily generalized to encompass 3D positioning.

3. Hybridisation methods: computing coverage

3.1. E-OTD and A-GPS as standalone

For 2D positioning, the E-OTD/OTDOA coverage is equal to the probability of carrier signals being received from at least 3 BSs. Hence

$$C_{E-OTD} = \Pr\left(N_{BS} > 2\right). \qquad (3)$$

In a similar manner, the A-GPS coverage can be computed as

$$C_{GPS} = \Pr\left(N_{SAT} > 2\right). \qquad (4)$$

For 3D location (i.e. including height), the number of necessary signal sources changes from 3 to 4 for both techniques.

3.2. Loose hybridisation

The simplest possible hybridisation consists in joining the resulting positions from E-OTD/OTDOA and A-GPS. If both positions are available, they can be combined in several ways in order to improve accuracy (e.g. weighted-averaged, simple selection of the most accurate, etc); although the combination procedure affects the accuracy of the location estimate, it does not have an impact on the coverage results. To determine the position, it is sufficient if at least one position as determined by a standalone technique is provided. Hence

$$C_L = 1 - \Pr\left[\left(N_{BS} < 3\right) \wedge \left(N_{SAT} < 3\right)\right],$$

$$C_L = 1 - \Pr\left[\left(N_{BS} < 3\right) \cdot \left(N_{SAT} < 3\right)\right]. \qquad (5)$$

3.3. Tight non-synchronized hybridisation

Tight hybridisation joins time measurements from incoming signals instead of from the resulting positions. Non-synchronized hybridisation assumes that there is no time synchronization between the terrestrial and satellite networks.

Figure 1 illustrates this approach, in which GPS satellites are all synchronized and terrestrial BS are also synchronized with one another, but there is no synchronization between the GPS and the terrestrial networks. In this scenario, a minimum of two signal generators in each network (i.e. 2 satellites or 2 BSs) are necessary to determine the position of an MS. Each pair of signal transmitters traces an ellipse and the intersection between these two ellipses indicates the position of the MS. A detailed description of the non-synchronized solution can be found in [11], in which the authors propose using Digital Audio Broadcast (DAB) stations instead of GPS satellites. However, their proposal can be easily extended to GPS and GSM/UMTS.

Again, the way in which the measurements are combined or weighted has an impact on the accuracy of the position estimate but not on the coverage. Tight non-synchronized hybridisation allows the MS to compute its position using two BS and two satellites. Thus, coverage can be computed as follows:

$$C_{NS} = C_L + \Pr\left[\left(N_{BS} = 2\right) \wedge \left(N_{SAT} = 2\right)\right],$$

$$C_{NS} = C_L + \Pr\left[\left(N_{BS} = 2\right) \cdot \left(N_{SAT} = 2\right)\right]. \qquad (6)$$

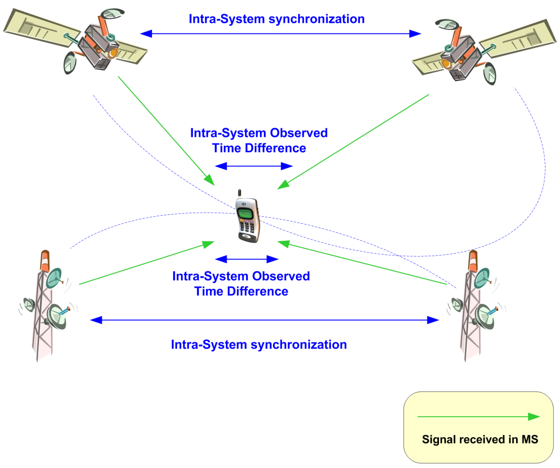

Figure 1: Location process in the Tight Non-Synchronized hybridisation approach.

3.4. Tight synchronized hybridisation

This method assumes that the terrestrial and satellite networks are synchronized. If this is the case, for triangulation purposes, satellites and BSs can be seen as belonging to the same network.

Figure 2 illustrates this approach and shows how global synchronization allows any combination of signal generators to be used to trace location ellipses. Therefore, the position can be computed at the MS based on signals received from 3 elements - either BSs or satellites [11, 12].

The cost of this synchronization is twofold: more clocks are needed in the LCS equipment for synchronization purposes (this cost has a minor impact since it is possible to use clocks that are already available in the BS) and additional signalling must be sent from the network to the MS. Several approaches for transmitting this synchronization assistance information between E-OTD and GPS have been presented in [13].

There are only three combinations of the number of received BS and satellites (SAT) that lead to a lack of coverage: 1 BS and 0 SAT, 1 BS and 1 SAT, 2 BSs and 0 SAT (0 BSs is not considered since we assumed that the MS is always covered by the cellular network). In all the remaining cases, the position of the MS can be provided. The coverage can be computed as follows:

$$\begin{aligned} C_S &= \Pr\left(N_{BS} + N_{SAT} > 2\right) = \\ &= \Pr\left[\left(N_{BS} = 1 \wedge N_{SAT} = 2\right) \vee \left(N_{BS} = 2 \wedge N_{SAT} = 1\right) \vee \right. \\ &\quad \left. \vee \left(N_{BS} > 1 \wedge N_{SAT} > 1\right)\right]. \end{aligned}$$

In a different way, this equation can be rewritten as:

$$\begin{aligned} C_S &= C_{NS} + \Pr\left(N_{BS} = 1\right) \cdot \Pr\left(N_{SAT} = 2\right) + \\ &+ \Pr\left(N_{BS} = 2\right) \cdot \Pr\left(N_{SAT} = 1\right) \end{aligned} \qquad (7)$$

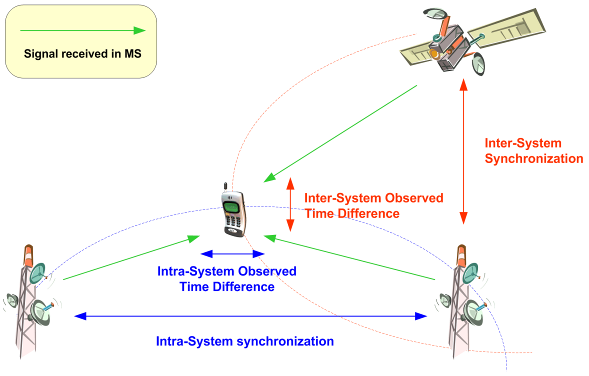

Figure 2: Location process in the Tight Synchronized hybridisation approach

4. Numerical results

This section provides numerical results to illustrate the consequences of the proposed analysis. Table I shows the PDFs of several scenarios of having a specific number of BS/GPS sources in sight. The data presented in Table I are reasonable hypotheses based on the authors' experience (unfortunately, field data are scarce in what literature is available). It must be noted that the poor performance of A-GPS in Table I is due to the constraints of the positioning of the MS, which is often within pockets, bags, urban canyons, etc. Some working hypotheses follow:

- The terrestrial network is GSM/GPRS with E-OTD.
- The PDF for E-OTD does not change from outdoors to indoors, although a slight coverage reduction should be expected in a true network. GPS coverage is strongly reduced from outdoors to indoors.
- The average number of BSs in sight to provide E-OTD coverage decreases from urban to suburban and rural. This agrees with the operators' practice of densely covering urban areas in which heavy traffic is expected.

Table I. Probability of signal available from a given number of BSs (for E-OTD) and satellites (for A-GPS) vs. scenarios.

	N_{BS}=1	2	>2	N_{SAT}=0	1	2	>2
Urban Outdoor	0.10	0.20	0.70	0.00	0.10	0.30	0.60
Urban Indoor	0.10	0.20	0.70	0.20	0.30	0.30	0.20
Suburban Outdoor	0.10	0.30	0.60	0.00	0.10	0.20	0.70
Suburban Indoor	0.10	0.30	0.60	0.10	0.30	0.30	0.30
Rural Outdoor	0.30	0.40	0.30	0.00	0.00	0.20	0.80
Rural Indoor	0.30	0.40	0.30	0.10	0.30	0.30	0.30

Table II shows the results of applying Equations (3)-(7) to each environment. Note the improvement obtained through hybridisation, especially when one or both methods are not able to provide a good coverage as standalone. One must also note the increase in coverage for the rural indoor environment, for which both techniques exhibit poor performance: coverage reaches 84% while each method has 30% as standalone.

Table II. Computed coverage for each hybridisation method vs. scenarios.

	$C_{E\text{-}OTD}$	C_{GPS}	C_L	C_{NS}	C_S
Urban Outdoor	0.70	0.60	0.88	0.94	0.99
Urban Indoor	0.70	0.20	0.76	0.82	0.91
Suburban Outdoor	0.60	0.70	0.88	0.94	0.99
Suburban Indoor	0.60	0.30	0.72	0.81	0.93
Rural Outdoor	0.30	0.80	0.86	0.94	1.00
Rural Indoor	0.30	0.30	0.51	0.63	0.84

To compute the overall network coverage, the results in Table II must be weighted-averaged according to Equations (2). The traffic share of each environment displayed in Table III assumes that in all environments 50% of calls take place indoors. For the territory share, it must be taken into account that, in urban areas, outdoor coverage (i.e. streets) represents a smaller percentage than indoor coverage (i.e. offices, houses). In rural environments, outdoor coverage (i.e. open fields) represents the bigger share.

Table III. Traffic (t_i) and geographical (g_i) proportion of each environment in the network.

	Traffic (t_i)	**Territory (g_i)**
Urban Outdoor	0.35	0.02
Urban Indoor	0.35	0.08
Suburban Outdoor	0.10	0.10
Suburban Indoor	0.10	0.10
Rural Outdoor	0.05	0.60
Rural Indoor	0.05	0.10
	1.00	1.00

Figure 3 displays the network coverage (i.e. for the whole cellular network). An interesting result in Table IV is that the three hybridisation methods studied in this paper tend to equal the traffic and geographical coverage for LCS in comparison with the non-hybridised case. For conventional voice and data services, the geographical coverage is always lower or much lower than the traffic one, since deployment starts in the most populated cities. Nevertheless, if terrestrial/satellite hybridisation is used, this mismatch is no longer an issue for LCS.

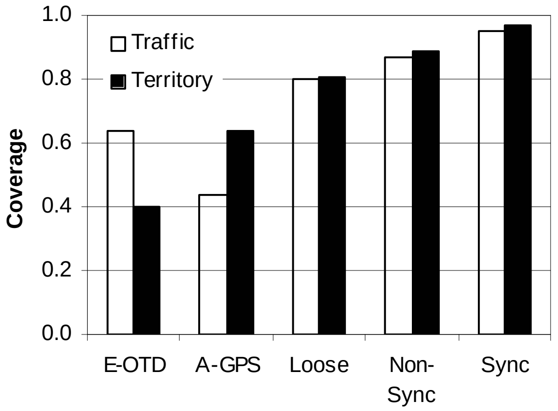

Figure 3. Computed service coverage.

5. Conclusion

The hybridisation of terrestrial and satellite positioning systems greatly improves service coverage, with improvements occurring even for the simplest hybridisation method (i.e. when the resulting positions of both methods are combined). More complex hybridisations are made possible by combining timing measurements from the terrestrial and satellite sources. The latter approaches provide better coverage, as they offer the best performance for synchronized hybridisation. The costs associated with optimum coverage are the hardware (i.e. clocks) and signalling (i.e. further synchronization assistance must be sent to the MS).

Another remarkable aspect is the similarity between the traffic and geographical coverage of the service, which contributes to fairness and to fulfil the regulators' requirements.

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