Precise Time Transfer in a Mobile Radio Terminal

Peter J. Duffett-Smith, *Cambridge Positioning Systems Limited*
Paul Hansen, *Cambridge Positioning Systems Limited*

BIOGRAPHY

Peter Duffett-Smith is the founding director of Cambridge Positioning Systems Limited and is its Chief Scientific Officer. He is also Reader in Experimental Radio Physics at the Cavendish Laboratory, University of Cambridge. His PhD is in Radio Astronomy and, with Paul Hansen, he is the inventor of the Matrix positioning method described in this paper.

Paul Hansen is VP of CPS's Terminal business and co-inventor of the Matrix technology. His PhD is in the field of kinematic GPS techniques. Prior to CPS, he worked on development of global DGPS systems for marine survey companies.

ABSTRACT

The degradation suffered by GPS installed in a mobile phone in shielded environments can be ameliorated to some extent by the use of network assistance (satellite information, GPS time information and coarse position) obtained from a fixed GPS terminal in the network, which can allow terminals to operate with GPS signals weaker by 20 dB or more. In this paper, we describe a new method of providing precise time aiding to mobile terminals used in un-synchronised communications networks such as GSM and W-CDMA ("3G") based on the Matrix positioning method by which the relative timings of network signals received by the handset are used to obtain both a terminal position and a network synchronisation map. This enables the terminal to carry precise GPS time information from open to shielded areas without requiring any GPS assistance from a network-based server.

Precise time aiding within a mobile communication terminal allows for GPS implementations of lower complexity and therefore of lower cost. This can be a crucial factor in mass-market take-up of satellite positioning technology in mobile phones.

INTRODUCTION

There are several methods in use, or proposed, for the positioning of mobile terminals in a communications network. They divide into two categories: (a) those methods which use signals from satellites, notably GPS, and (b) those methods which use signals from the network. The satellite methods offer excellent performance in open spaces in terms of accuracy and coverage, but work poorly, if at all, inside buildings or at street level in high-rise urban settings. This is in part because of the increased scattering of the satellite signals, but is mainly because the satellite signals are weak: in open spaces at the surface of the Earth the signal strength from a GPS satellite may be around about -130 dBm. On the other hand, the methods which use signals from the network are generally less accurate in open spaces, but they work nearly everywhere since the strengths of the signals received by a mobile terminal from the network are typically 60 dB higher. Furthermore, the accuracy of network-based methods is largely insensitive to environment.

One of the ways of overcoming the weakness of the satellite signals is to provide the satellite receiver in the terminal with assistance information – satellite ephemeris and almanac data, time aiding, and position aiding. This information is usually generated within the network and sent to the terminal on request, and can result in a detection gain of more than 20 dB, allowing weaker satellite signals to be detected and hence increasing the coverage of the satellite positioning service. It also decreases the time taken for a position to be obtained, which can otherwise be many tens of seconds. Some recent implementations of GPS receivers within mobile terminals have been further hampered by poor antenna performance and noisy receivers, sometimes adding a further 10 dB of attenuation. Even in excellent implementations, the orientation of the GPS antenna makes a big difference to the signal level at the receiver input terminals. Under these circumstances, the assistance information is required even to obtain reasonable positioning service in 'normal' conditions.

Because of these limitations, an A-GPS positioning service is usually provided with a fall-back method which can provide the terminal's position in the event that the A-GPS method fails. In CDMA networks, which are synchronised, the fall-back method is typically Advanced Forward-Link Trilateration (AFLT). This uses the known positions of the base stations, known signal transmission timings, and measured signal reception timings to calculate a terminal's position. Other mobile communication technologies, such as GSM and W-CDMA, use un-synchronised networks, i.e. ones in which the transmission time offsets of the signals radiated by one base station relative to another are unknown. In this case, the fall-back method is typically Cell-ID, i.e. the terminal's position is reckoned as the position of the serving base station, or the centroid of the serving cell. The particular problem of the Cell-ID method is that it is quite inaccurate. In well-implemented systems, the error can be as little as about one quarter of the inter-cell spacing, i.e. ranging from several hundreds of metres in dense-urban environments to ten km or more in the countryside. There is then not a good fit between the A-GPS method and its fall-back, so that a user experiences a sharp degradation in accuracy on moving from an open to a shielded environment, often exacerbated by having to wait a long time before the A-GPS method fails and the inaccurate position is reported.

The problems encountered by A-GPS systems are illustrated in Table 1. Two such systems deployed commercially in Japan were tested side-by-side. One of the systems was associated with a CDMA 2000 network (which was synchronised), and was supported by time aiding. The fall-back positioning method was Advanced Forward-Link Trilateration (AFLT). The other system was associated with a PDC network, without time aiding (the network was unsynchronised), and with Cell-ID as the fall-back positioning method. The table gives the radius in metres of the circle centred on the true position containing 67 % of the results, both for an area with open sky (the PDC and CDMA based systems were equally good here) and for each system averaged over a number of dense urban outside environments. The A-GPS yield is also shown, this being the percentage of all results for

Where	67% (m)	A-GPS yield (%)
Open Sky	15	100
Urban outside (CDMA)	68	74
Urban outside (PDC)	114	30

Table 1: A-GPS test results from a Japanese city

which GPS was used rather than the fall-back method. As expected, the systems worked very well in 'open-sky' conditions, but suffered both in accuracy and yield in more challenging environments. The impact of time aiding is reflected in the figures for A-GPS yield. However, even with time aiding (CDMA), no GPS result was achieved within a time-out period in more than a quarter of the tests. Without time aiding (PDC), this figure rose to nearly three-quarters. It is clear that both the time aiding and the accuracy of the fall-back method were important influences on the user experience of these positioning services.

Another disadvantage of A-GPS is that it is expensive to incorporate into mobile phones. As volumes rise, so the cost of implementation reduces, but even so the service is likely to be restricted to 'high-end' terminals. To be sufficiently cost-effective for the mass market, the silicon cost needs to be no more than about $1 per device, and the positioning service must then provide ubiquitous coverage, fast response, and reasonable accuracy everywhere with well-mannered degradation from open to shielded areas. One way of reducing the complexity of the GPS receiver is to provide it with the GPS time accurate to within several microseconds. This greatly reduces the search space for the detection of satellites so that fewer correlators are needed, and hence a smaller silicon footprint. The time to fix and battery drain are also reduced.

The Matrix positioning method, a development of the standardised E-OTD (GSM) and OTDOA (3G) methods, uses signals transmitted by the network in order to find the position of the mobile terminal. Unlike its E-OTD/OTDOA predecessors, it needs no additional hardware in the network (except for the SMLC server needed by all positioning systems), and in particular does not need any Location Measurement Units (LMUs) [1]. The standard version of Matrix works by determining the relative positions of two or more terminals so locating them simultaneously. However, recent improvements to Matrix provide for good positioning performance with just one terminal, the so-called 'Solo Matrix' feature. As a by-product, a timing map of the network is produced within the system, and we show below how this can be used provide precise GPS time aiding in unsynchronised networks. Thus Matrix can enhance satellite positioning systems by providing time and position aiding, and when combined with GPS the technology is referred to as 'Enhanced GPS' (E-GPS).

In this paper, we describe the Matrix method, provide results of field trials, and describe two implementations showing how a terminal containing a GPS receiver can carry precise GPS time information around with it.

HOW MATRIX WORKS

A block diagram of a standard Matrix system is shown below in Figure 1. A small software upgrade is installed in a terminal which measures the relative receive times of the signals from surrounding network transmitters. These timings are occasionally requested by the Matrix SMLC from 'anonymous' terminals, and are used to calculate and maintain a list of network transmission time offsets (the network timings). When a position request for a specified target terminal is generated by an application, the terminal responds with its timing measurements, which the Matrix locator then uses in conjunction with the network timings to calculate the position of the terminal [2,3].

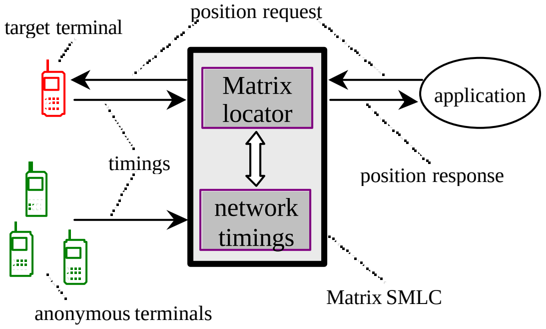

Figure 1: A standard Matrix system

The way in which the Matrix method operates can be illustrated further by considering the equations governing it. For simplicity, we restrict our analysis to the two-dimensional case, i.e. the terminals and base stations all lie in a plane. We specify the position of the i^{th} terminal in a set of M active terminals by the vector $\boldsymbol{r}_i$ relative to an arbitrary origin in the plane, and the position of the j^{th} network transmitter in a set of N transmitters by the vector $\boldsymbol{b}_j$ relative to the same origin. The time, t_{ij} at which a signal is received by terminal i from transmitter j is then given by

$$ct_{ij} = \left|\boldsymbol{r}_i - \boldsymbol{b}_j\right| + e_i + a_j \,,$$

where $i = 1\ldots M$, $j = 1\ldots N$, e_i is the time offset of the terminal's internal clock (expressed as a distance), a_j is the transmission time offset of the transmitter (also expressed as a distance), and c is the radio wave propagation speed. The values of t, e and a are all expressed relative to an imaginary universal uniform clock.

This defines a set of MN equations in $3M+N-1$ unknowns. (The -1 term arises because, in practice, the absolute values of the timings have no meaning, so that one of the e_i or a_j values can be set to zero without loss of generality.) Provided that MN is at least as large as $3M+N-1$, a solution to the set can exist, and if the geometrical disposition of the base stations and terminals allows it the Matrix™ SMLC calculates all the values of $\boldsymbol{r}$, e, and a, maintaining the network timing model with the values of a, and discarding the other values.

The position of a target terminal can be calculated from its measurements of just three or more network transmitters provided that the corresponding values of a can be obtained from the network timing model. Minimum configurations for generation of the network timing model include (N = 2, M = 5) and (N = 3, M = 4), but in practice the timing measurements from many terminals are used in the matrix. In addition, the accuracy of the timings is improved by the in-built averaging of the measurements from many terminals.

SOLO MATRIX

Although the transmitters in a GSM or W-CDMA network are not synchronised with each other (i.e. their relative transmission time offsets are undetermined), they nevertheless display a high degree of coherence in practice. We have found that measurements made several hours apart can be used together in a single Matrix calculation. That is to say, the reports from the anonymous terminals need not be simultaneous. This opens the prospect of tracking a single moving terminal.

A block diagram of Matrix system exhibiting the Matrix Solo feature is shown in Figure 2.

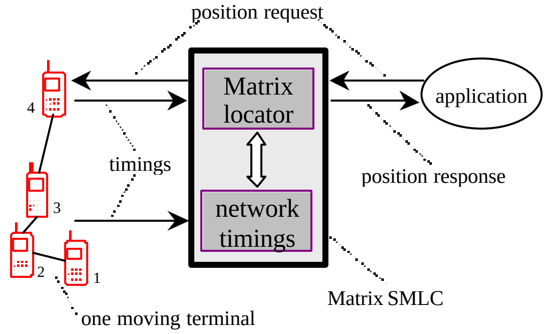

Figure 2: Solo Matrix

In this instance, the network timing model is maintained by the timing measurements from a single terminal which moves from position 1 to position 4 within the coherence period of the network. The measurements sent by the terminal from positions 1, 2, and 3 are used to maintain the network timing model just as in a standard Matrix system, and the measurements sent from position 4 are used to calculate that location. Indeed, the measurements from all four positions can also be used in a single calculation to find all four locations, and hence the track of the moving terminal.

In practice, the terminal software includes the provision of current and historical measurements, so that the location of a now-stationary terminal can be found if it moved sometime in the past. A standard Matrix system naturally includes the Solo Matrix feature, hence providing good performance even when the number of active terminals is very low.

TEST RESULTS

Standard Matrix systems have been tested around the world many times in many different GSM networks. Some specific examples are given in Table 2. In summary, the accuracy of a standard Matrix system operating on a GSM network is 50 to 100 m at the 67 percentile. Since the network signals are so strong (compared with GPS signals for example), the terminal makes its timing measurements in much less than one second. The calculation in the SMLC takes no longer than a few milliseconds, so the response time of a Matrix system to a position request is almost entirely limited by the transit time of the messages. We have measured the response time in several networks using GPRS to be under 3 seconds. The yield figures indicate that Matrix operates nearly everywhere that a voice call can be placed, including inside buildings in urban centres.

Where	67% (m)	Yield (%)
Cambridge	56	99
Central London	81	100
European city (inside)	55	100
Asian city (outside)	80	98
Asian city (inside)	91	100

Table 2: Some Matrix test results

The Solo Matrix feature has also been tested on many different networks in several parts of the World. Shown in Figure 3 is one example. A single Matrix-enabled GSM handset was carried in the pocket of a pedestrian walking around Cambridge. The scale is in metres and the blue grid is at intervals of 1 km. The handset was configured to send its timing measurements to the SMLC every minute using SMS. There were no other terminals used in this test. The positions calculated using the Matrix Solo feature are shown by the dots joined together by straight-line segments.

The accuracy of a Solo Matrix track depends on a number of circumstances, but in general the error is between 1 and 2 times greater than for a standard Matrix system operating in the same area. The accuracy of Matrix and Solo Matrix in W-CDMA is expected to be about two times better than in GSM. Early measurements on a live 3G network in the UK have supported this claim [4].

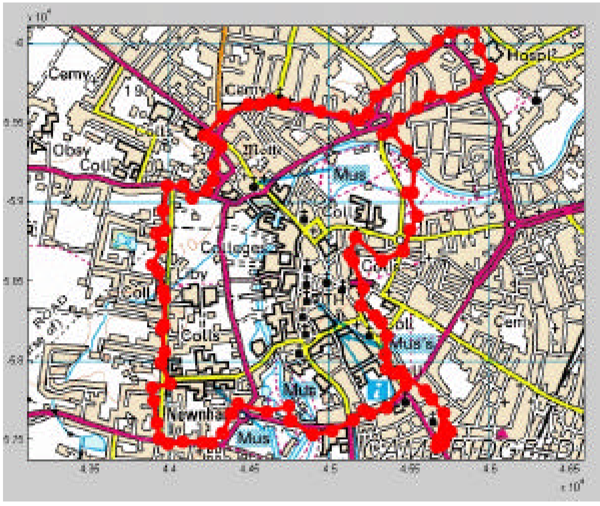

Figure 3: A Solo-Matrix track

MATRIX ENHANCED GPS POSITIONING

It is evident from the foregoing discussion that Matrix provides both the position of a terminal and the relative transmission time offsets of the network transmitters. In the case of Solo Matrix, this is achieved using the measurements just from a single terminal. The choice of where the calculation is made (i.e. the location of the SMLC) is clearly arbitrary and, given a powerful enough processor, could be located inside the terminal itself. In Figures 1 and 2, the SMLC is shown as a network-based node. Figure 4 shows the SMLC implemented inside the terminal. Figure 5 shows the calculation function transferred to a network-based SMLC, with a network timing list mirrored within the terminal.

The terminals shown in Figures 4 and 5 include satellite positioning hardware (such as GPS) in addition to the hardware normally associated with its operation as a communications terminal. In Figure 4, the box labelled SMLC represents a software program running on the terminal's processor which carries out the functions of an SMLC operating in the Solo Matrix mode. The network timings (the values of a) are calculated in the Matrix locator module and stored as a list in the network timing model. Solo Matrix operation is therefore confined entirely within the terminal (although it also will need occasional access to a database of network transmitter positions and their radio frequencies, which may be kept on a server in the network). The 'SMLC' element within the terminal is able to compute the position of the terminal within the constraints of Solo Matrix operation, and also maintains the list of the relative transmission time offsets of the network transmitters, with a typical accuracy of better than 300 ns. These timings, together with the Matrix-derived position of the terminal, constitute a high-stability clock which does not reside within the terminal, but which can be read at any time. This is a rather subtle point. Unlike a system in which a high-stability clock is carried around with the terminal, the ‘clock’ in this case is remote, but because the terminal is able to calculate its position (using Matrix), and hence its distance from any of the transmitters, the list of relative transmission time offsets provides an accurate relative time reference.

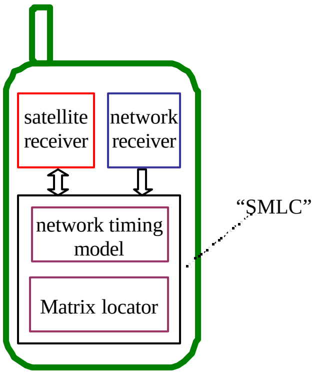

Figure 4: Elements of an autonomous Matrix-enhanced satellite terminal

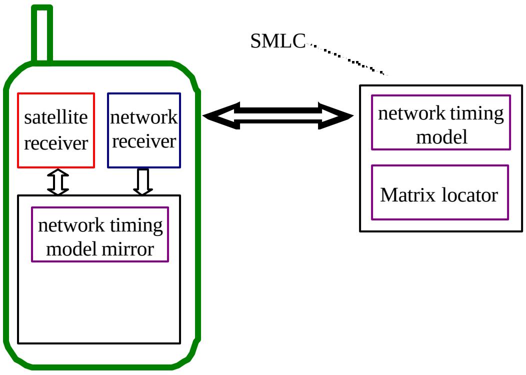

Figure 5: Elements of a network-aided Matrix-enhanced satellite terminal

At this point the ‘clock’ is un-calibrated since the transmission time offset of any network transmitter is undetermined in GSM or W-CDMA, so there is no calibration with respect to any recognised time-base such as GPS time. However, the terminal of Figure 4 incorporates a satellite receiver which, although remote from the ‘clock’ in this system, can nevertheless be used to calibrate it. When the terminal is in ‘open-sky’ conditions, the satellite receiver can obtain a full position and time solution without aiding. The time and position can then be used to calibrate the signals from one of the network transmitters. This in turn calibrates the rest of the transmitters in the timing model list, since the list contains their relative transmission time offsets so that calibration of one determines the calibration of all. At a later time, when the terminal has moved to a position where the satellite receiver needs assistance in order to measure enough satellite signals for a position solution, the signals from a network transmitter can be used, in conjunction with the calculated Matrix position and the calibrated list of transmission time offsets, to provide the satellite receiver with calibrated accurate time information. This sequence of events is listed in Table 3 below.

First, in open-sky conditions:	• A standard GPS fix is obtained • A Solo Matrix fix is obtained at the same time • The network timing model is established in the handset • The relative timings are known well within 1 µs • The offset of GPS time is measured with respect to one or more transmitters in the list
Later, when time aiding is needed:	• A Solo Matrix calculation made • The GPS time is calculated from a received network signal, the measured GPS time offset, and the network timing model • Precise time and coarse position aiding is provided to GPS

Table 3: Autonomous Matrix-enhanced GPS operation

The mode of operation just described and listed in Table 3 enables the terminal to operate autonomously, indeed even without registering on the network, but suffers from several disadvantages in practice. These include (a) the need to carry out the Matrix calculations in the handset with its corresponding processor load, (b) the need to have a database of network positions and frequencies within the handset, and (c) the limitation to Solo Matrix operation of being unable to use the additional timing measurements from many anonymous terminals. A better solution is to have the Matrix calculation made in a network-based SMLC, and to duplicate in the terminal only the network timing model. This overcomes all three of the disadvantages mentioned above. Better still is to use the calculated Matrix position to adjust the network timing values for the times of flight of the signals from the respective transmitters to the terminal. This removes the need for the Matrix position to be transmitted to the terminal, and minimises the processor load. Table 4 below lists the sequence of events in this configuration.

First, in open-sky conditions:	• A standard GPS fix is made • A standard or Solo Matrix fix is made at the same time • The network timing model is established in the SMLC • The adjusted network timing model is sent to the handset, and stored as a mirror list • The relative timings are known well within 1 μs • The offset of GPS time is measured with respect to one or more transmitters in the list
Later, when time aiding is needed:	• A standard or Solo Matrix fix is made • The network timing model is established in the SMLC • The adjusted network timing model is sent to the handset, and stored as a mirror list • The GPS time is calculated from a received network signal, the measured GPS time offset, and the adjusted network timing model • Time (and position) aiding is provided to GPS

Table 4: Network-aided Matrix-enhanced GPS operation

CONCLUSION

The system described in this paper gives a terminal containing satellite positioning hardware, operating in an unsynchronised network, the ability to receive accurate time aiding. This is important for the following reasons:

- Accurate time aiding reduces the complexity of the satellite receiver. Some solutions provide for thousands of on-chip correlators to carry out parallel searching for satellite signals in time and frequency space in order to reduce the precision with which satellite time needs be known in advance. Less complex chips are less expensive, so accurate time aiding reduces the cost of the terminal. Cost is a critical factor in the successful commercial deployment of Location Based Services.

- Accurate time aiding (along with the associated position aiding) reduces the time to obtain a fix. The speed with which a position is returned to the user is a critical factor in the user experience of a Location Based Service.

- Satellite acquisition time increases as the RF environment worsens. Accurate time aiding therefore reduces the battery drain and (in some implementations) the processor load.

Other benefits of knowing the satellite time in advance include a 2 to 3 dB of gain in the decoding of the satellite signals through alignment on the bit edges, and fast resolution of ambiguous pseudo ranges without using Doppler information.

A further advantage of the system described in this paper is that a good match is achieved between the accuracy of the GPS system at the point where it begins to fail (accuracy reduced because of multi-path) and the fall-back method, so that the user experiences a seamless and graceful degradation in the accuracy of the Location Based Service from that achieved by GPS in open-sky conditions to the sub-100 m accuracy of Matrix in GSM.

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