Measurements of the effects of multipath interference on timing accuracy in a cellular radio positioning system

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Abstract: The authors present a quasi-interferometric technique for measuring the flight times of signals broadcast by global system for mobile communication (GSM) transmitters, together with measurements made using the technique in and around Cambridge, UK. The data are used to determine the errors associated with GSM signal arrival times in various environments. The majority of the timing errors in all signal environments lie in the range $-1$ to $+1.5$ $\mu$s, with the tails of the distributions extending beyond $\pm 3$ $\mu$s. The authors show that these large timing errors are caused by the distortions of the cross-correlation peaks used to determine the signal arrival times as a result of coherent multipath interference. Models of timing errors, based on Cauchian distributions, fit the experimental data better than those based on symmetrical or skewed Gaussian functions. This has implications for attempts to combine GSM and global navigation satellite system measurements using Kalman filters.

1 Introduction

Radio positioning systems incorporated into mobile handsets have become commonplace. Those available in 2010 use global positioning system (GPS) as the positioning engine, supplemented by coarse position estimates based on base-station tower locations. GPS devices require assistance inside buildings and other shielded spaces in order to centre and narrow their search windows to find the attenuated satellite signals within acceptable waiting times. Cellular radio signals can provide both position and time aiding\cite{1} to a GPS receiver, but of course it is important to know the errors associated with measurements of the times of arrival of the cellular signals.

Works by previous authors\cite{2–6} have demonstrated that the errors incurred when using global system for mobile communication (GSM) signals to determine the position of a cellular handset are typically in the range of 50–500 m, depending on the environment and other factors. In this paper, we present a new method of measuring the signal flight time from a GSM transmitter to a mobile receiver, together with the results of a series of measurements using it at various locations in and around Cambridge, UK. Previous works in this field include studies based on simulated data\cite{6, 7}, measurements made using channel sounders rather than GSM base stations\cite{8} and developments of correlator-processing techniques\cite{9–11}. There are relatively few reports of studies using measurements of the GSM signals themselves.

2 Positioning systems, apparatus and methods

2.1 GSM radio positioning systems

Radio positioning systems such as GPS are based on the estimations of the ranges to several satellites from the receiver using time-of-flight measurements. This is possible because the timings of the satellite signals are known accurately. Radio positioning systems, which use the signals radiated by the base stations of a GSM system, cannot
Positioning methods such as enhanced observed time difference (E-OTD) [12] and Matrix [5] make use of data gathered from several base stations at two or more receiver locations to accommodate the lack of information about the transmission time offsets of the base stations. In GSM, handsets are synchronised with the serving base station using the extended training sequence (ETS), a code word transmitted on the logical broadcast control channel (BCCH) every 50 ms or so. Both E-OTD and matrix use the time of receipt of the ETS in their positioning calculations. This is estimated using the position of the peak of the cross-correlation between the received signal and a local copy of the ETS. An interpolation is often used to improve the precision of the measurement, and although more sophisticated algorithms have been tried, the narrow bandwidth of the GSM signal, combined with the effects of multipath interference, generally conspires to yield little improvement. Indeed, there is evidence to suggest that the simple peak-measuring method yields the best average positioning accuracy because both the E-OTD and matrix methods use time differences, in which common offsets have reduced the effect. Correlator-processing techniques also require greater computational power than simply determining the maximum value of a cross-correlation function. The results of this paper are therefore based on measurements of the interpolated correlation peak.

2.2 Measuring signal flight times

An obvious method of measuring the flight time of a signal between a GSM transmitter and a mobile handset some distance away is to use a radio interferometer. One antenna is placed next to the transmitter, while the other is placed at the handset's position. The signals from the two are then correlated to find the time offset between them. In practice, this method is inconvenient as it requires two sets of synchronised apparatus and two experimenters (or some other means of operating and securing the apparatus at the unmanned end).

For these and other reasons, we have devised an alternative quasi-interferometric method using just one set of apparatus. Our method relies on the excellent stability characteristics of the base-station’s controlling oscillator [13], and the regularly-repeating ETS signal. A schematic diagram is shown in Fig. 1. An unamplified quarter-wave dipole antenna, providing about 2 dBi of gain, was connected to an IFR 2319E radio-frequency receiver and digitiser (Rx) phase-locked to an Efратom FRK-H rubidium frequency standard (Rb). This also controlled the timings of the data recordings by triggering captures at exact multiples of the ETS repeat rate. Under ideal conditions (no interference or clock errors), the recorded ETSs would therefore appear at the same positions in the data stream every time for a stationary receiver. The ETS positions were found by cross-correlating the data stream with a copy of the ETS word. Maximum values of the modulus of the interpolated cross-correlation marked the positions of the ETSs in the record, referred to hereinafter as the ‘ETS peaks’. One million complex samples were recorded by the apparatus per data capture at a rate of 2.04 Msamples s$^{-1}$, providing 10 or 11 consecutive ETS peaks. The GSM signal bandwidth of about 140 kHz was therefore over-sampled. The sinc-interpolated cross-correlation was up-sampled by a factor of 20, giving a sample period of 24.5 ns corresponding to a distance of 7.35 m at the speed of radio waves. The digitiser provided 12-bit quantisation, resulting in a dynamic range of 72 dB.

The base station identification code (BSIC) of each GSM transmitter, broadcasts with the ETS, was decoded each time to ensure that a given ETS came from the intended transmitter. Whenever a BSIC did not decode correctly, the record was inspected to determine whether the corresponding ETS peak was one of the set. This process ensured that the most heavily corrupted ETS peaks, which contributed to the tails of the timing error distributions, were detected and recorded while simultaneously protecting against erroneous data from co-channel interference. Successful decoding of a BSIC guaranteed that the signal strength was above a threshold of about $-93$ dBm [14], with a signal-to-noise ratio better than 9.

For a stationary receiver, variations in the position of an ETS peak were caused by (a) instabilities in the transmitter and/or receiver frequency reference, (b) transmitter-based errors, (c) changes in the propagation path and (d) signal interference effects at the transmitter or receiver. As the receiving equipment was moved relative to the transmitter, the signal’s flight time changed and the ETS peak positions in the data recordings varied accordingly. If an ETS peak sample number corresponding to zero distance...
from the BTS is represented by \( C \), and the peak position sample number measured at a test point by \( P \), then the time-of-flight to the receiver can then be estimated from

\[
\text{time of flight} = \frac{P - C}{S}
\]

where \( S \) is the sampling frequency.

This quasi-interferometric method did not filter out any slight variations, oscillations, non-linear drifts or other unwanted behaviour affecting the transmission times, but instead relied on the transmitter’s frequency reference being highly stable. Previous work by the authors [13] had shown that the stabilities of certain GSM transmitters in Cambridge were similar to those of atomic frequency standards, and the same transmitters were used to produce the results discussed here.

An ETS peak position was expected to be stationary with time for a stationary receiver only if the frequency references in the transmitter and the measuring apparatus both remained exactly on their nominal frequencies, or drifted in exactly the same fashion such that their difference remained the same. In practice, neither of these situations was likely, but the systematic error caused by a constant offset between the oscillator frequencies manifested itself as a constant slope on the timing data. This linear drift was easily corrected by performing calibration measurements at a fixed, uncluttered location close to and within direct line of sight of the transmitter at the beginning and end of each measurement set. Between a pair of calibration recordings, the apparatus was taken to several test positions, both indoors and out, where further recordings were made. A set of recordings at the test positions, and the bounding calibration recordings, are collectively referred to as an experiment. After an experiment, all of the recordings were cross-correlated with a copy of the ETS to yield a time series of ETS peak positions. An example of this is shown in Fig. 2. Range is plotted vertically in metres with zero shown by the horizontal dotted line, and test-position reference letters increase to the right. Each ‘pedestal’ represents the ETS peak times measured at a test position in three half-second recordings spaced about 3 s apart, resulting in at least 30 ETS peaks. As expected, the measured range increased with distance from the transmitter. The expected range, representing the geometric time-of-flight at the speed of radio waves, is shown by the horizontal line at each pedestal.

Fig. 3 shows a map of the test positions A–M used in the experiment of Fig. 2. Tests at A, B, C, D, K, L and M were made in areas which were relatively free of multipath interference. Hence there was little variation in the positions of the ETS peaks measured during the tests. However, tests F, I and J were made at points with severe and variable multipath interference, with the result that the ETS peak positions showed large apparent fluctuations. We discuss this further in Section 4.

A series of experiments (Table 1) was carried out in and around Cambridge, England over the period May 2006–September 2006. The test-point locations were determined using a Sirf Star III GPS device or, in the case of the indoor experiments, accurate floor plans. Each GPS determination was averaged over 50 s. The GPS horizontal dilution of precision value was always less than 1.5, with a minimum of eight satellites in view, giving a root mean square horizontal error of about 5 m. This error estimate was verified by displaying the GPS locations on a high-resolution map for the operator to examine during the experiments and corresponds to about 17 ns error in signal flight times, which is small compared to the timing errors associated with GSM multipath interference.
3 Results and discussion

3.1 Definitions of the outdoor environments

The outdoor experiments (see Table 1) were performed under four environment types, characterised as rural, suburban, light urban and mid-urban based on features such as the number, typical size and spacing of buildings [15]. We did not carry out any experiments in dense urban environments because Cambridge city does not feature such a region.

3.2 Results

The data from the experiments listed in Table 1 are plotted as histograms in Fig. 4. The timing errors are calculated from the differences between the ranges measured using the GSM timing measurements and the geometric (straight-line) times of flight calculated from the positions of transmitter and receiver. The histogram bins are 50 ns wide and a five-bin moving average has been performed on each histogram before plotting in order to smooth the data.

All five plots contain a significant proportion of data with negative values, corresponding to ETS peaks that give apparent signal flight times shorter than the line-of-sight flight times. This behaviour can also be seen in the example pedestal plot shown in Fig. 2. Such values are not caused by measurement noise (around ±80 ns indoors and around ±50 ns in an open environment) or by systematic errors (estimated to be smaller than about ±45 ns). They are the result of distortions of the shape of the cross-correlation peak caused by coherent multipath interference, and are a consequence of using the maximum value of the cross-correlation function as the estimator of the signal arrival time (see later).

The histograms show that the timing error distributions for rural and suburban environments were narrower than for the urban and indoor environments. Cambridge and its environs lie mostly on flat land, and the rural environment timing error distribution is representative of an uncluttered

<table>
<thead>
<tr>
<th>Environment</th>
<th>Number of experiments</th>
<th>Total number of test locations</th>
</tr>
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<tbody>
<tr>
<td>rural</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>suburban</td>
<td>4</td>
<td>113</td>
</tr>
<tr>
<td>light urban</td>
<td>2</td>
<td>76</td>
</tr>
<tr>
<td>mid urban</td>
<td>2</td>
<td>62</td>
</tr>
<tr>
<td>indoor</td>
<td>2</td>
<td>77</td>
</tr>
</tbody>
</table>
agricultural region. The majority of the rural and suburban values lie in the range $-0.5$ to $+0.5$ m, corresponding to ranging errors of $\pm 150$ m. The majority of the urban and indoor values lie within the range of $-1$ to $+1.5$ m, corresponding to errors in the range $-300$ to $+450$ m. All the environment types contain a small population of errors exceeding $\pm 500$ m. The timing error distributions are similar to Cauchian rather than Gaussian distributions. This is illustrated in Fig. 5, which shows the Cauchian and Gaussian distributions best fitting the rural data set. The ratio of the chi-squared statistics corresponding to the Cauchian and Gaussian fits for each environment type is given in Table 2, demonstrating that the Cauchian distribution provides a better fit to all of the data sets.

These timing-error distributions suggest that filters based on Gaussian errors, such as the extended Kalman filter [16], are not optimal for timing-based radio positioning when the maximum value of a cross-correlation function is used to measure signal arrival times without any multipath

Figure 4 Plots of the normalised histograms of the timing error measured in each environment.

Figure 5 Plots of best-fit Cauchian and Gaussian distributions overlaying the rural timing-error data set. The graph is plotted with a logarithmic y-axis to amplify detail in the tails of the distributions. The plots demonstrate that the timing errors are reproduced better by the Cauchian distribution.
mitigation. Filters based on a Cauchian timing error distribution should provide better performance (e.g. suitably-tuned particle filters [17] or Gaussian-sum Kalman filters [18]). It should be noted, however, that the use of these timing error distributions in innovation gating (the discarding of measurements deemed to be spurious when compared with expectation based on prior measurements and knowledge of the system dynamics) could be employed by a simple extended Kalman filter to improve performance.

The three distinct and equally-spaced peaks in the indoor timing error distribution may have been caused by signals propagating within and reflecting back along the corridors before scattering to the receiver. It is also possible that signals were scattered from other buildings near the Cavendish Laboratory and entered the surveyed building with additional path lengths of 100 m or more. However, there was no clear correlation between these distinct peaks and any specific areas within the building, suggesting that the indoor signal environment is complex and that the 'choice' of signal propagation path varies on a fine spatial scale.

4 Effects of multipath interference on narrowband positioning systems

The tails of the timing-error distributions measured in the experiments were caused by coherent multipath interference. This can be seen in Fig. 6, which shows ten consecutive ETS peaks recorded at a stationary receiver. The distortions observed were likely to have been caused by changes in the propagation paths altering the relative phases and delays of the multipath components at the receiver antenna, thereby changing the shape of the ETS peak. The peak positions of the ten cross correlations plotted in Fig. 6 vary over a range of about 2.5 µs, corresponding to 750 m apparent distance from the transmitter. The distorted peak position can lie on either side of the undistorted, line-of-sight peak position, resulting in both positive and negative values. The cross-correlation peak can also become so distorted that it splits into two peaks, giving rise to extreme values in the tails of the timing-error distributions. We can now explain the rapid variation in measured range at position F in Fig. 2. At this location the multipath environment was such that a dual-peak cross-correlation function was generated. Small variations in the signal path lengths or environmental conditions over the capture period resulted in variations in the relative heights of the two peaks, leading to the position of the maximum value of the cross-correlation function jumping discontinuously between extreme values.

Table 2 Ratios of the chi-squared test statistics for Cauchian and Gaussian fits to the timing error distributions

<table>
<thead>
<tr>
<th>Environment</th>
<th>Ratio of chi-squared test statistics (Cauchian distribution:Gaussian distribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rural</td>
<td>1:25</td>
</tr>
<tr>
<td>suburban</td>
<td>1:54</td>
</tr>
<tr>
<td>light urban</td>
<td>1:1.3</td>
</tr>
<tr>
<td>mid urban</td>
<td>1:5.4</td>
</tr>
<tr>
<td>indoor</td>
<td>1:8</td>
</tr>
</tbody>
</table>

Figure 6 Moduli of ten consecutive SCB peaks recorded during a single measurement
This plot demonstrates how the large timing errors observed in these experiments are caused by distorted cross-correlation peaks.
It should be noted that the widths of the cross-correlation peaks are determined by the signal's coherence length, and therefore its bandwidth. The scale of coherent multipath errors is also then determined by the signal bandwidth. Higher signal bandwidths result in narrower timing-error distributions. It is also expected that the timing-error distributions will become more asymmetrical as the bandwidth increases. This is because only the positive tail is influenced by delay spread (incoherent interference).

5 Conclusions

1. A quasi-interferometric experimental method is described, which allows GSM signal flight times to be measured directly using a single set of apparatus.

2. Measurements of the differences between the expected and measured signal flight times in various environments have been presented. The corresponding timing-error distributions follow Cauchian distributions.

3. The observed timing errors are caused in part by distortions of the ETS correlation profile attributed to coherent multipath interference.

6 Acknowledgment

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7 References


[12] GSM Specification: ‘Digital cellular telecommunications system (phase 2+); location services (LCS); (functional description) – Stage 2’ GSM 3GPP 03.71 version 8.0.0 Release, 1999


