Analysis and Migration of Location-Finding Methods for GSM and 3G Networks

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Abstract **This paper initially reviews the current range of location techniques on GSM networks, such as Cell-ID, GPS, A-GPS, Time Difference of Arrival (TDOA) and E-OTD (Enhanced Observed Time Difference). It shows how these techniques can be applied to the future migration to 3G networks. The paper shows practical experiments of current accuracy of location and how these vary depending on the actual location of the mobile device. Along with this, the paper discusses new enhancements to TDOA (Time Difference of Arrival) and Cell-ID methods using improvements to the Timing Advanced signal. These are compared with practical experiments, along with typical accuracies.**

***Index Terms*— Locating-finding, GSM, 3G**

I. Introduction

Many mobile phone network providers are investigating new methods of generating income, and location-finding has great potential in supporting location-based services [1]. This might include location-based advertising, mobile inventory management and mobile financial services. There is, obviously, constraints to these technologies, such as changes in business strategies, investment risk, limitations in mobile devices, networking problems, infrastructure constraints, security concerns, and a general user distrust of mobile applications [2].

There is generally a lack of published work in this area, and it is often confusing as to the accuracy and relevance of the methods used in mobile phone tracking. This paper thus focuses on the main methods that can be used to provide location information, especially for the GSM network, and to show how these techniques can be used to determine the accuracy of the location-finding technique.

The best technique for location-finding is, of course, the GPS (Global Positioning System) system which has good accuracy for virtually any area of the world. Unfortunately, it can be relatively expensive to implement, and does not give good coverage around and within buildings. Users can thus be tracked in an open environment, but their trace may be lost as soon as they enter a building, or if the path between them and the GPS satellites is obstructed. Mobile phone techniques, on the other hand, are generally less expensive to implement, and can give reasonable accuracies. These techniques can thus be useful to network operators in providing services based on geographical locations, and also to users, such as in tracking field service engineers, or in tracking transport services [1]. A major worry in mobile communications, though, is that users often distrust the security of mobile devices [2]. For this, a context-aware mobile information system (CAMIS) has been developed [3], which uses a non-intrusive *push*[1] technology to deliver information to mobile users using a cell-broadcast.

Generally, positioning technologies can be defined in terms of:

- **Performance**. This is based on the accuracy of the positioning method that gives different levels of accuracy and hence aims at different market sectors. For example, fleet managers do not require a high level of accuracy, so this method can simply find the nearest antenna to the device. However, emergency services, such as mountain rescue or ambulance services, are likely to require more accuracy, such as determining the distance that the device is away from several antennas.
- **Complexity**. Sometimes combining and deploying two or more location technologies gives results that are more accurate. These positioning technologies can be grouped under complexity, and are commonly known as hybrid systems.
- **Implementations requirements**. Some implementations require extra implementations in the existing systems to achieve some degree of accuracy, such as in the software requirements of the handsets, or in the hardware requirements of the mobile network.
- **Investment**. This is a major factor, and it depends on the amount of additional services that the network can provide for in the future, and their required level of accuracy.

Nokia [4] define four different service area sizes for the accuracy. The requirement of the application typically defines which of these is required. They are:

- **Town-specific**. This would basically involve determining the city/town that the device is located in, and would be able to differentiate the location of different towns, such as between Edinburgh, UK and Livingston, UK.
- **District-specific**. This would involve determining the location between different districts, such as determining between different districts of Edinburgh, UK, such as the South of Edinburgh and the West of Edinburgh.
- **Quarter-specific**. This would involve determining the quarter of the location, such as between different areas of

[1] A push technology involves information being sent to the mobile device without the user actually requesting it, where as a pull technology involves the user actually requesting the information. There is currently a trend towards a more pro-active system of using push technologies to send information to the user, without them requesting it.

a city such as between the Gorgie and the Morningside areas of Edinburgh.

- **Street-specific.** This would involve determining the actual street of the device.

The calculation of location can either be done by the handset (in the handset-based mode), or by the network (in the handset-assisted mode). In the handset-assisted mode, the handset makes measurements, and reports these back to the network as a Network Measurement Report (NMR), which calculates the handset position.

II. Location-finding Methods

This section outlines some of the practical techniques using in locating handsets used in GSM networks, and the following section shows how these methods are being extended into 3G networks.

A. Cell-ID (Cell Identity) and Cell ID with TA

The most basic positioning finding methods used in a GSM network is based on cell identification (Cell-ID). This is a network-based positioning method, where the cell that the handset is registered to. This information is available in the network and at the handset. Cell-ID is then converted to a geographic position using knowledge of the operator's network, such as coverage database at the serving mobile location centre (SMLC). The accuracy level thus generally depends on the cell size, but may also depend on other factors such as the wireless network type (*GSM* or *PCS*), cell type (*omni-directional* or *sectored*), cell kind (*macro cells* – large-scale cells - or *pico cells* – small-scale cells), and so on. It has the advantage that it supports every legacy handsets and roaming subscribers. A sectored cell uses a number of antennas in the cell, and these provide sector information. The larger the number of sectors, the more accurate the location of the device will be. For example a three-antenna cell, gives a sector coverage of 120° for each sector. The accuracy will thus be ±60°. When a handset is registered to an omni-directional cell, the location of the handset becomes exact location of the mast, that is, centre of the cell and the coverage area (cell size) of that mast becomes the accuracy level (Figure 1). In case of sectored cell, the handset's location is calculated using mathematical algorithms.

With E-Cell ID, the handset makes measurements of its operating conditions, and sends them to the network for hand-over decisions. This network measurement report (NMR) contains the estimated power level at the handset from the serving cell, and also from neighboring cells. The power level measured at the handset can then be used to estimate the location, based upon simple propagation models and/or network planning tools.

Similar techniques can be used using the Timing Advance (TA) signal parameter, instead of NMR. The TA is a measure of the handset range from BTS[2] (Base Transceiver Station), and have a resolution of 550m and improves accuracy level in larger (omni-directional and sectored) cells, as in GSM 900. With TA, the handset registers with at least three base stations which send out a timing signal, for which the handset sends back a result to the network for a position calculation.

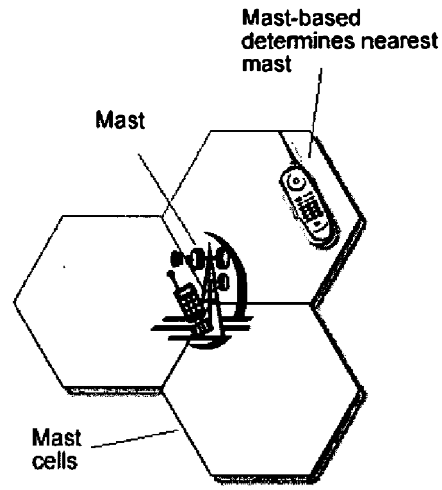

Figure 1: Cell site with sector

B. TOA (Time-of-arrival) and TDOA (Time Difference of Arrival)

TOA works by the handset bouncing a signal back off the base stations, or vice-versa. Since radio waves travel at the speed of light (c), the distance (*d*) between the handset and base station can be estimated from the transmission delay, that is, half the time delay between transmitting and receiving the signal. This, however, locates the handset as being on a circle with a radius d, with the base station at the centre of the circle. If the estimate is made from three base stations, there will be three circles that intersect at the handset.

TDOA technique is time-based and quite similar to TOA. It works by either measuring the relative arrival time in the handset of signals transmitted from three base stations at the same time; or measuring relative arrival time transmitted by the handset at three base stations. The difference of arrival time defines a hyperbola, with the loci at the two base stations. As three base stations are used, there are three sets of time differences which creates three hyperbolic equations that define a single solution (Figure 2).

TDOA is sometimes preferred to TOA as, in most implementations; there is less data to be exchanged over the wireless connection. Precise synchronization of base stations is required for this technique to work. In case additional accuracy is required, a serving base station instructs the handset to hand-off, which causes the handset to transmit a new registration message. This registration message gives the base station a new set of data to make a second estimate.

C. E-OTD (Enhanced-Observed Time Difference)

In this time-based technique the handset measures the arrival time of signals that are transmitted from at least three or more base stations (Figure 3). The time measurement capability of E-OTD is a new function on handsets. In the handset-assisted mode, the timing measurements made by the handset are then transferred to the Serving Mobile Location Centre (SMLC) using standardized LCS signaling. The measurements returned are related to the distance from each base station to the handset and the position of the handset is estimated using

[2] Base Transceiver Station (BTS) is a mast with antenna

triangulation. In handset-based mode, the position calculation function is in the handset, and the position is returned to the SMLC. The position of each base station must be accurately known to perform triangulation and estimate the position of the handset. Also, the transmission times of each base station must also be accurately known. In GSM network, which is not synchronized, the base station transmission time must be measured using a network of Location Measurement Units (LMUs). These are essentially modified mobile devices, optionally with a GPS receiver, placed in a fixed geographical position, with the capability to perform E-OTD measurements and return them to the SMLC.

E-OTD accuracy is dependent on cell density, cell plan, multi-path, interference, noise, LMU performance, and cell site position accuracy. In this technique the accuracy does not degrade much indoors, and it performs well in high base stations density areas. Conversely, E-OTD performance is degraded areas with low base stations density.

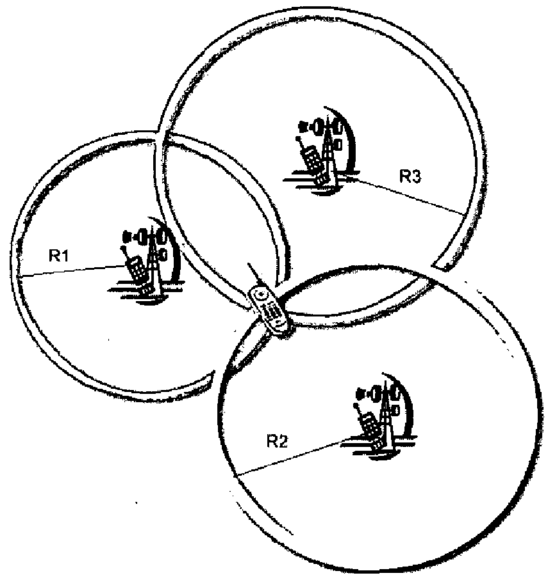

Figure 2: Intersection

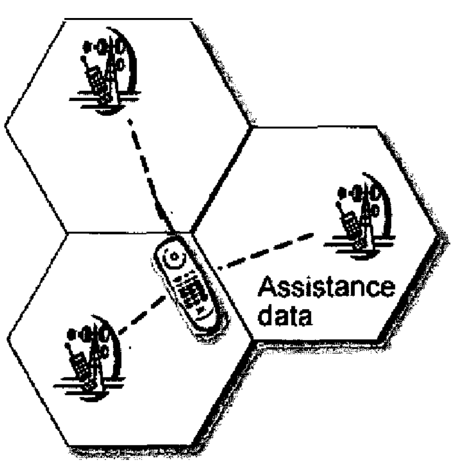

Figure 3: E-OTD

D. A-GPS (Assisted – Global Positioning System)

Like E-OTD, A-GPS is also a time-based technique in which the handset measures the arrival time of signals transmitted from three or more GPS satellites. In general, the information decoded by the GPS receiver from the satellites is transmitted to the handset through the radio network, bringing improvements for the time-to-first-fix (which is the initial time for the first location measurement) and battery life – as the handset no longer needs to search for and decode the signals from each available satellite. Removing the need to decode the satellite signals also enables detection and TOA estimation, which allows it to provide position estimates under foliage, within cars, in most outside environments, and many indoor environments. A-GPS also provides good vertical accuracy and velocity estimates. Signals of GPS assistance data to the handset may take 10 seconds, but, once received by the handset, assistance data is useful for up to four hours.

III. 3G Methods

3G networks offer enhanced methods in location-finding, but these, to protect investments, are likely to integrate with existing GSM methods. The proposed standard architecture by the 3GPP (3G Partnership Project) for locating finding involves:

- **GMLC** (Gateway Mobile Location Centre). This is responsible for the interface between the application and the network, and converts the location information into the required format.
- **SMLC** (Serving Mobile Location Centre). This is responsible for actually making the measurement, and involves some knowledge of the cell layout and geographical information.
- **LMU**. This is used with E-OTD/OTDOA (OTD Of Arrival) and allows for the synchronization measurements. It can either be integrated in the mobile device, or distributed over the network.

With 3G, the four main methods are likely to be:

- **Cell ID.** This is identical to Cell ID used in GSM methods, and the accuracy will relate to the size of the cell.
- **Cell ID with RTT (Round Trip Time).** This will use the RTT signal to determine the round trip time, and fits in well with existing methods in GSM networks. A sectored cell makes the measurement more relevant.
- **OTDOA.** This is a The UMTS standardized method which is similar to E-OTD as used in GSM networks. A typical technique is IPDL-OTDOA (Idle Period Down Link - Observed Time Difference of Arrival) [4], which is proposed by Nokia. It requires an LMU, and can thus be expensive to implement. With OTDOA the mobile device measures from several based stations at a time, and the propagation delay determines the distance. The technique thus requires that the devices can hear three base stations.

- **A-GPS**. This is based on the existing A-GPS technique, and will require a GPS hardware module. It requires a much less investment for the network operator than OTDOA, but there are problems within buildings and in areas of poor radio coverage. It yields an accuracy of around 10m in open areas [7]. Unfortunately, in urban environment the line of sight path between the mobile station and the satellites can be blocked which reduces the accuracy and availability. Along with this the integrated GPS module increases terminal cost, size and power consumption. This, thus, reduces the deployment of this technique.

OTDOA measures the time difference of signals of base station pairs, and requires a minimum of three base stations for a two-dimensional coordinate solution. As UMTS has a larger bandwidth, OTDOA provides a more accurate measurement than the corresponding time-delay E-OTD technique, used in GSM networks. Unfortunately its accuracy reduces due to multi-path propagation and non-line-of-sight environment, such as in urban situations. When this occurs the signal delays will thus not correlate with the actual geometrical delays which reduces the delay estimation and thus the location accuracy.

Along with path propagation problems another weakness of OTDOA is a hearability problem, where the weak signals from base stations which are far away from the mobile station are swamped by nearer base stations. This effect can be reduced with idle periods [4, 8], where the base stations turn their transmitter off which allows blocked stations to transmit their signal.

IV. EXPERIMENT

The purpose of this section is to show how much the accuracy of the location-find can vary, and also the methods that can be used to determine the accuracy of the location-finding method. Experiments were conducted in a city location, and in the rural location. In almost all situations, the rural location gives the worst accuracy as the cell sizes are at the largest. The procedure used in defined in [5] and uses:

1. Nokia Handset 7210 with NetMonitor[3].
2. GPS receiver (Benefon) or from network operator's WWW site. [6].
3. Microsoft MapPoint.

A. Results outside a city using GPS to locate the device

Figure 4 shows an experiment in the Borders of Scotland (around Newton St. Boswells), and Table 1 summarizes the results. The two concentric circles are a set of minimum and maximum distance from each base station. Since each time slot, when converted to distance value, represents 550 m, the mobile station can possibly be either at the start of the time slot, or can be right at the end. Hence, the distance between the two concentric circles is 550 m. According to the Figure 5, the handset location area is shaded and has a radius of 310 m. Thus the resolution accuracy, in this case, is 310 m.

[3] NetMonitor is an administrative software tool for Nokia mobile phones that is mainly used for monitoring network and phone parameters.

Table 1: Calculation results of TA for three BTSs

Cell-ID	OS Grid	TA	Distance (km)	BCCH
28393	E357070 N6329040	4	1.925 – 2.475	45
4121	E365510 N632220	12	6.325 – 6.875	105
22747	E361450 N626975	10	5.225 – 5.775	49

B. Results around a city using WWW-based location finding

In this case the mobile device will be based in one location and be static (the location is based on the post code EH10 5ET). Using the postcode [6], it is possible to get a diagram of Edinburgh with the MMO2 base stations and the cell global identity (Figure 6). Using the Nokia 3210 handset and NetMonitor, the channel frequency, timing advance, cell global identity and signal strength can be recorded and the results outlined in Table 2.

As the timing advance to each base transceiver station is known and by using equation, it is possible to workout the maximum and minimum distance to each BTS. The difference between each maximum and minimum distance is 550 m, which is exactly the difference of one timing advance. First thing that has to be noted is that Edinburgh is a heavy populated urban area, so there is no shortage of base station (which are represented by triangles). In the experiment there is also no shortage of nearest neighboring cells and NetMonitor was able to pick up the serving cell and all eight of the nearest neighboring cells. For the purpose of the experiment, it was decided to show just the serving cell and four of its nearest neighbors.

These results show the theory of Cell-ID + TA working but there are some inaccuracies with the results. The most obvious is that [6] only gives a rough estimation of the location of a BTS. The actual location could be up to 50 m from where the BS is shown on the diagram, what is needed is the ordinance survey grid co-ordinates (latitude, longitude) that are accurate to a few meters. GPS was not used to get an exact location of either the BTS or the position of the MS it makes it hard to validate the exact accuracy of the MS.

Table 2: Results from Cell-ID with TA experiment

Cell-ID	BCCH	TA	RX Level	Distance from BTS (m)
15493	83	1	35	275 – 825
11586	79	1	25	275 – 825
17947	65	2	19	825 – 1375
11577	87	2	17	825 – 1375
11578	71	3	16	1375–1925

C. Results in a remote location

This experiment is conducted in a rural area, where there is a small population and a low usage of the network, which means that the type of cell used will be a large macro cell with a large coverage area. The area chosen is Tain which is a small town, 35 miles north of Inverness (Figure 7). The cell global identity is 16648, which is shown on the map and obtained from [6]. This experiment shows the weakness of cell global identity as a location finding technology in a rural area. As there are no other cells within range to perform a handover, which gives information on neighboring cells. This experiment does confirm that the mobile station is in the coverage area of the home cell, which covers more than 615 km square. Although the data collected can still be 'pushed' to a location based server, the value of the information returned to the user would be minimal as all it could do was give a very rough estimate of the mobile station location, which in this case is anywhere located within the circle.

V. CONCLUSIONS

The migration of location-finding methods from GSM to 3G will bring enhancements to the existing methods, but there are still many issues to be solved. A major element is that the resolution of the location method typically depends on the size of the cells used. In and around the cities, the cell sizes tend to be small, so that the mobile station can be tracked with a reasonable accuracy. Unfortunately in remote areas the cell sizes can be large, thus the location finding methods often give poor accuracies. A-GPS methods are obviously the best techniques for locating the mobile station, but it does suffer when there is poor radio reception, especially within buildings.

As has been seen, A-GPS suffers from poor coverage in urban environments and also within buildings. On the other hand, OTDOA suffers from problems associated with non-line-of-sight radio propagation, and in hearability issues. An alternative approach, which reduces the multi-path problem, is Database Correlation Method (DCM) [9]. It uses a database which uses an *a priori* collection of measures of measured or predicted signal levels, along with other location-related data on the defined service area [10]. This technique compares signal measurements from the mobile station with signal estimations in the database. It has been shown that an accuracy of 44 m is possible in GSM networks. If used in UMTS networks the technique could use wide bandwidth to defined radio channel power delay profiles (PDP).

In conclusion, it is likely that mobile phone operators will used several methods, which will typically define the accuracy required, such as [4]:

- **Basic**. This will include Cell-ID and Cell-ID with RTT to give accuracies which relate to the size of the cells. In urban situations these accuracies are likely to be reasonable, but in remote situations these are likely to be poor. The applications of this might include tourist and fleet management applications.
- **Enhanced**. This will use methods such as OTDOA and E-OTD which provides enhanced location-finding methods, and gives a wide coverage, including within buildings. Applications of this are likely to include the tracking of children, car emergency response and asset tracking.
- **Extended**. This uses A-GPS techniques and gives the highest accuracy. Unfortunately it suffers from a lack of coverage within buildings. Typically applications are likely to include stolen car recovery and vehicle navigation.

In general, as has been seen in this paper, the actual accuracy will typically relate to the actual environment of the device.

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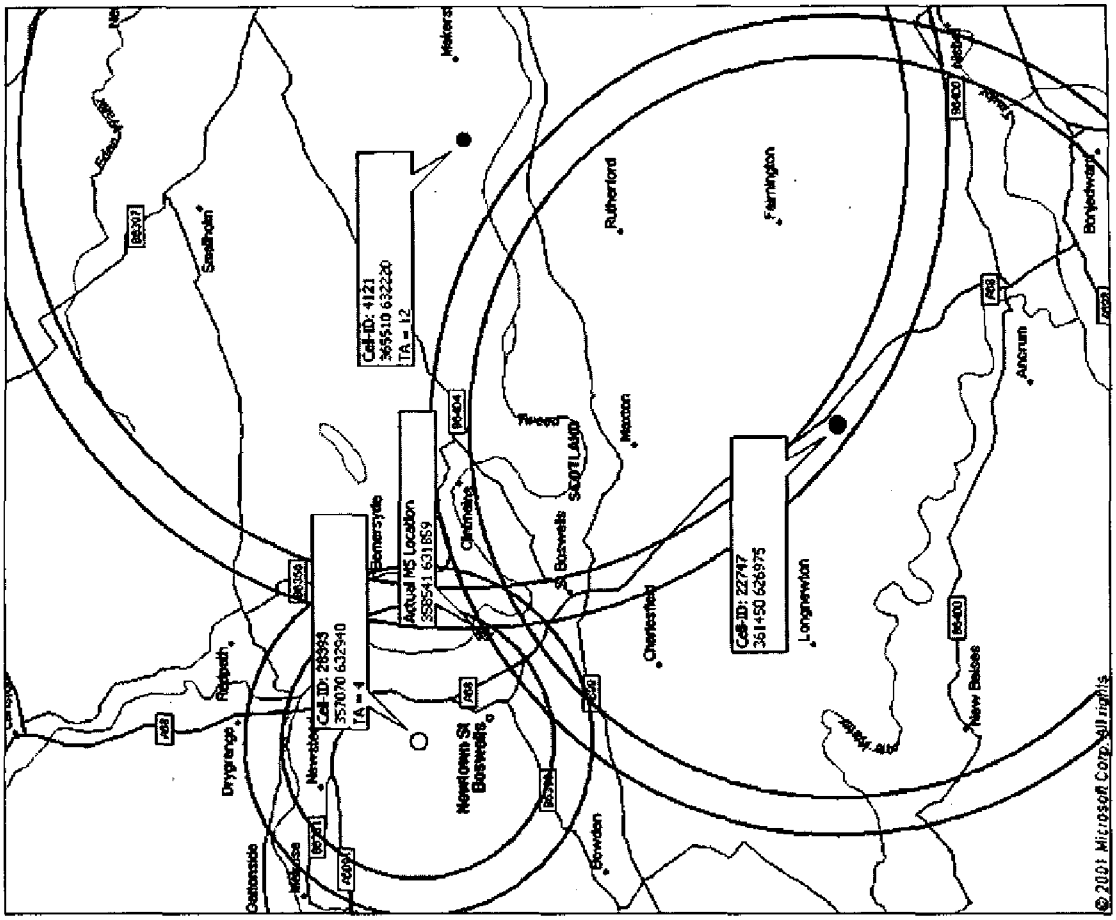

Figure 4 Results outside a city (Newton St. Boswell, UK)

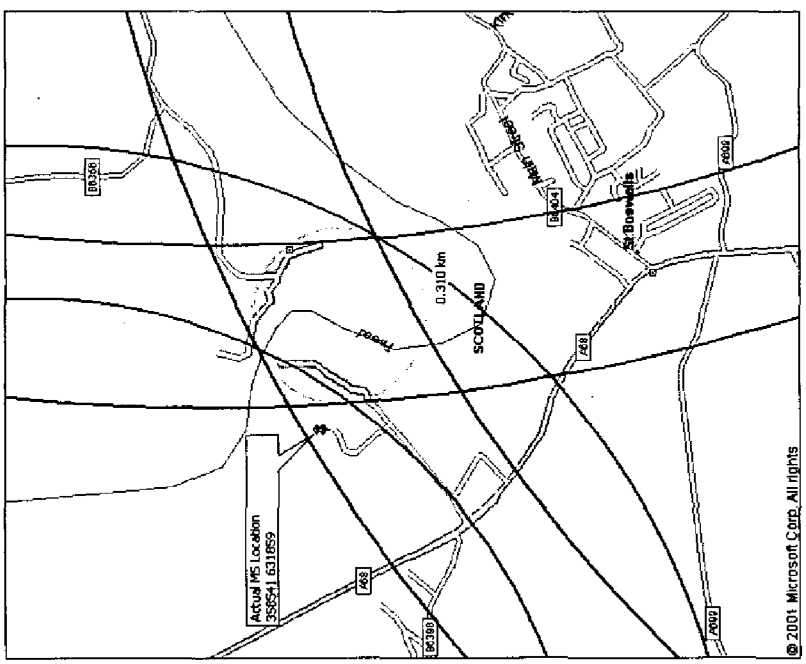

Figure 5 Results outside a city (Newton St. Boswell, UK)

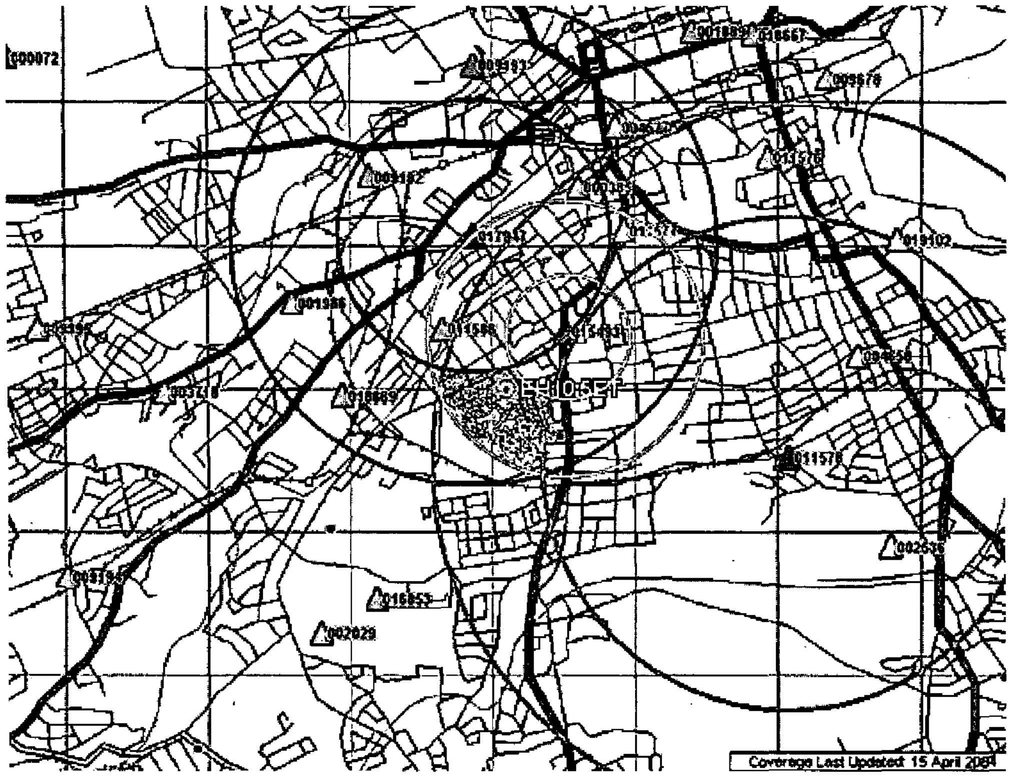

Figure 6 Results within a city (Edinburgh, UK)

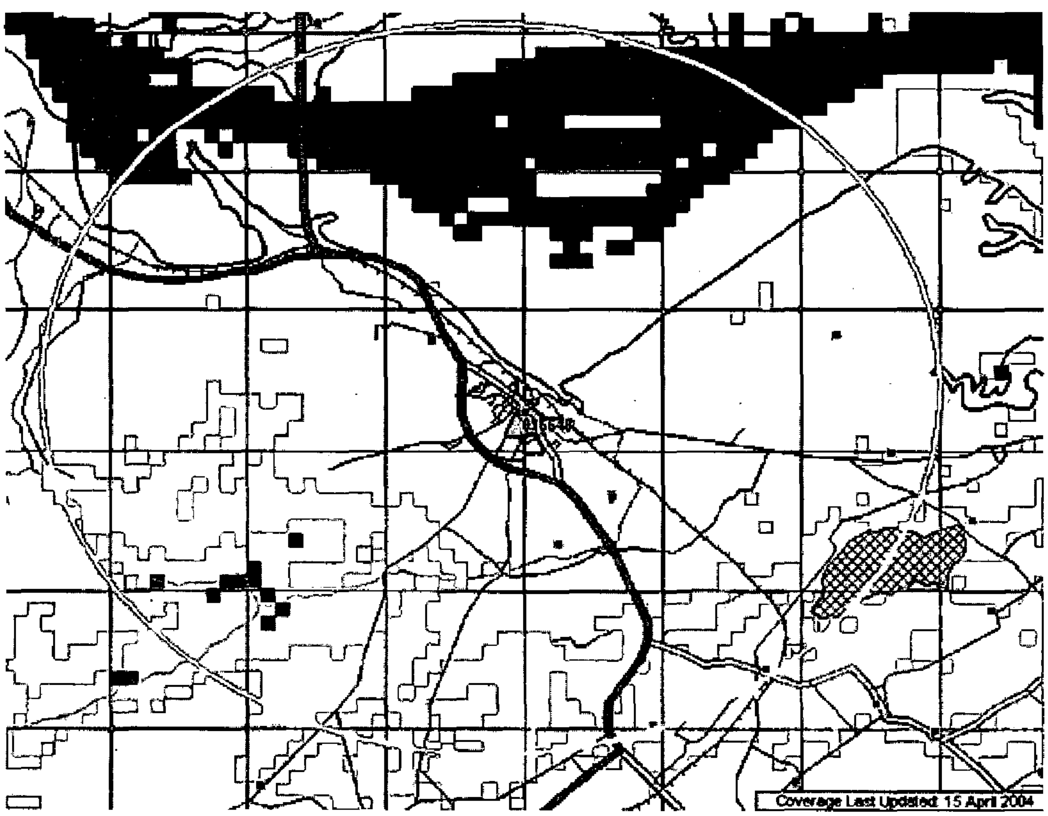

Figure 7 Results within a remote location (Tain, UK)