Achieving Improved Network Subscriber Geo-Location

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Abstract

Future disaster and emergency management requirements are currently under discussion in the US and Europe that will require mobile phone network operators to locate their subscribers to a high level of accuracy within a short time period. Current deployed mobile phone geo-location systems are required to locate the caller to within 125 m. Future systems will require an order of magnitude better accuracy.
This paper proposes a method to achieve improved location accuracy with the addition of carrier phase analysis and accurate time of flight techniques to current systems. The resulting combination of technologies has been analysed using a simplified model to benchmark and compare the subscriber location estimate against existing solutions.
The system described in this paper shows the potential to meet the emerging disaster and emergency management requirements in complex radio frequency environments.

Keywords

Geo-location, SyncE, IEEE1588 PTP, RF navigation, carrier phase analysis.

1. Introduction

Current disaster and emergency management applications require mobile phone network providers to locate the physical position of their subscribers if they contact the emergency services; in the case of US, the enhanced emergency alert (E911) legislation requires the network providers to locate the caller to within 125 m 67 % of the time (Reed et al. 1998). Next Generation 911 (NG911) is likely to require more accurate and more reliable position estimation of the user calling the emergency services, likely to be < 10 m up to 95% of the time (DTRITA 2013). This legislation will lead to a requirement for network operators to be able to quickly locate subscribers in many challenging environments.

One of the main challenging environments of operation is likely to be locating users in dense urban environments and urban canyons (ground level urban areas with very limited direct visibility of the sky/satellites). These areas typically have very dense subscriber populations and complex radio frequency (RF) environments.

Typical RF problems encountered in dense urban environments include high multipath effects, poor line of sight (Including poor GPS coverage), localised areas of low signal strength and considerable inter-channel interference.

This paper will investigate the viability of combining mature and developing technologies in order to provide a more accurate subscriber location estimate over a wider range of environments than can be obtained from any single technology.

The remainder of this paper is broken into the following sections. Section 2 reviews the current deployed capability for mobile phone geo-location. Section 3 provides a summary of the commonly applied approaches to coupling mature technologies to provide geo-location services. Section 4 provides an overview of a novel system that could be deployed in addition with current geo-location systems to provide an increased level of system accuracy. Method of overcoming the main challenges of this system are described in section 5. Section 6 details the simulation work carried out to verify the described approach. The results obtained from this simulation are provided in and section 7. Sections 8 and 9 provide information on future work and conclusions gained from the paper.

2. Current Deployed Capability

Current E911 compliant geo-location based systems are largely based on time difference of arrival (TDoA) systems. The most accurate and widely deployed system currently used is the AT&T uplink TDoA (U-TDoA) system. (AT&T 2013).

This system relies on sensitive time synchronised location measurement units (LMUs) located at each base station. The LMUs monitor each subscriber's uplink data channel when placing a call. The individual LMUs are time synchronised by GPS and communicate over the inter-base station network to calculate a subscribers position. This system commonly provides geo-location accuracy of around 50 m when the subscriber has a line of sight view of at least 3 network base stations. (True Position 2011).

3. Current Research Areas

The current state of the art in mobile phone subscriber geo-location can be separated into three main areas: RF based, peripheral device based and hybrid of both systems. Many peripheral and hybrid systems require the use of ancillary sensors within the subscriber's handset. Due to a lack of standardisation in the peripheral devises available on any mobile phone and the high coverage required to meet the emerging requirements, this review will cover RF based systems which use typical mobile phone RF devices only.

The network based approach relies on using the characteristics of both the mobile phone network and other RF systems, such as Wi-Fi, to provide a geo-location estimate.

Perhaps the most commonly applied technique to provide a geo-location estimate for subscribers within a mobile phone network is to use timing based techniques such as time of arrival (ToA) (van der Bij and Lipinski 2012) or time difference of arrival (TDoA) (Locata 2013). All time based systems however suffer from several drawbacks. Firstly in areas with poor line of sight from the transmitter to the receiver, the signal cannot take a direct path. This causes significant error at the receiver. Additionally, the reflection of signal produces a multipath environment and associated reading, leading to further measurements errors.

Another approach to network based geo-location is to use an angle of arrival (AoA) approach. This approach commonly requires the calculation of the angle that a signal is received from (Niculescu and Nath 2003). If the angle of the subscriber is known from three or more base stations, the users location can be calculated by creating an intersect. Again this approach has several inherent problems, firstly a non-line of sight signal path will cause intersect errors. Secondly, the method of accurately locating the angle of arrival is not trivial and involves the use of sectored, rotation or electronically steerable antennas, all of which have considerable angular measurement errors.

Frequency and carrier phase analysis may also be used to estimate a subscriber's location (Roxin et al. 2007). Frequency based analysis typically relies on the motion of the subscribers to allow the Doppler shifts in their signals to be tracked. The drawback to this method is the fact that the location of slow moving or stationary subscribers will drift over time. Meanwhile, carrier phase analysis relies on the monitoring of the carrier signal phase of a source RF signal. The drawbacks of this technique are that the signals monitored need an accurate clock to provide reliable phase analysis and that the carrier signal can be affected lowering positional accuracy.

Another RF based approach that can be taken is to monitor certain network properties, from generic signal strength to data recognition, including such as cell IDs or signal fingerprinting (Kjaergaard 2010). This family of approaches has one main drawback: The subscriber system must have either a pre-determined database of network topology data or have acquired it via a lengthy simultaneous localisation and mapping (SLAM) procedure. Both of these approaches are difficult to implement in practical scenarios where either RF topology changes rapidly without the network operators knowledge or there is no time to build up a complex SLAM calibration scheme.

GPS receivers are currently integrated on many mobile phones. The task of relaying the GPS information over the network to the network operator is trivial. There are however limitations to using GPS in urban environments. To operate successfully, the receiver needs a clear line of sight view of at least 4 GPS satellites. In most locations, this requires a wide field view of the sky, which is not available in many urban canyon environments. It is worth noting at this point that, although there are many urban areas where there are less than 4 satellites in direct line of sight, many densely populated areas are likely to still allow visibility of 1 or more satellites due to the good constellation spread of existing GPS satellite networks.

Success has been made in combining a single GPS receiver with ToA and carrier phase analysis to determine a geo-location estimation [9]. This approach combines mobile phone network ToA and carrier phase analysis to provide a position estimate in the absence of a full set of GPS satellites. Due to limitations in the measurement accuracy of the phone network component of this system, location estimates only provided an uncertainty of 345 m 95% of the time.

The concept of combining GPS and terrestrial RF systems can be improved selecting a terrestrial signal with better transmission properties than those found in mobile phone networks.

4. Improving U-TDoA Resolution with Short Wave Radio Phase Analysis

The proposed method relies on several layers of techniques with varying accuracy levels that complement each other in a typical urban environment, starting with U-TDoA for coarse acquisition and adding in other techniques to provide added robustness and accuracy.

The system assumes that a U-TDoA system is in operation and can achieve a positional accuracy of < 50 m in good conditions with a clear line of sight to the subscribers. It is also assumed that the area has a good level of coverage from a short wave digital Digital Radio Mondiale (DRM) signal. The DRM radio service is a shortwave radio service that uses a modulated carrier wave frequency of 5-6 MHz (ETSI 2009), providing a wavelength of approximately 50 m. Due to the commercial nature of the DRM service, transmitter location is optimised in urban environments to allow good population coverage.

It is possible in non-multipath environments, with GPS clock accuracy, to carry out phase analysis on the recovered transmission carrier wave with a phase noise of <10 % (Carvajal et al. 2011). This provides a location accuracy of ≈ 5 m if a clear signal is received.

It has been mentioned that the carrier phase technique requires a GPS level clock accuracy of ≈ 100 ns (Dana 1990). This only requires visibility of 1 GPS satellite. This external time source may also be provided in indoor environments by a GPS time repeater system.

It can be seen that DRM carrier phase analysis, supported by the GPS clock pulse, can be overlaid onto the existing U-TDoA system and can improve the locational accuracy by an order of magnitude.

The problem still remains that the system would provide poor results in an area of high multipath propagation of the DRM signal.

5. Combatting Multipath

To combat the effects of multipath in the signal, an extra layer of geo-location techniques is required in the system. A typical multipath environment is considered in Figure 1.

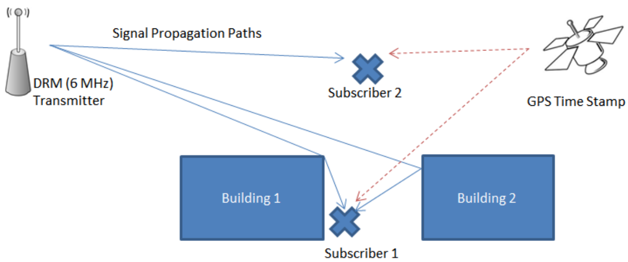

Figure 1: Typical Urban Environment with Multiple Signal Paths

It can be seen in Figure 1 that subscriber 1 does not have a direct line of sight with the DRM transmitter and is receiving both a reflection and a refraction of the transited signal. Receiving both signals, with a slight time delay increases carrier phase noise and makes the position estimation within the DRM signal less accurate.

If the phase analysis is carried out sufficiently frequently (at least 8 samples per sine wave), the subscriber system can calculate the quality of the carrier phase analysis. In the scenario shown in Figure 1, subscriber 2 has a good line of sight with the DRM transmitter, so consequently could easily determine that it has a good Gaussian distributed positional accuracy. Conversely subscriber 1 knows that it has a poorly distributed carrier phase signal and is likely to have a poor positional accuracy distribution.

In this case, subscriber 1 can gain a relative position from subscriber 2. This is possible by using the IEEE 1588 precession time protocol (PTP) in conjunction with ITU Synchronous Ethernet (SyncE) standard. The combination of the PTP time plane and SyncE frequency plane to estimate ToA can provide timing accuracies of ≈ 4.5 ns. (Ouellette et. al. 2011) proving a relative positional accuracy of < 2 m between the two users. From this relative navigation solution, it is possible for subscriber 2 to maintain a geo-location with an estimation error of < 10 m, even in an area of high multipath and poor line of sight with any external reference.

6. Simulation Details

The aim of the simulation is to calculate the positional estimation accuracy of subscribers in a system where carrier phase analysis and ToA geo-location are used simultaneously to determine a user's geo-location in areas of both low and high multipath.

The following major limitations and assumptions have been applied to the simulation model; the subscribers are not moving; During reflections and refractions there is no frequency shift to the affected signal; The received signal strength is suitably high and free from interference, including atmospheric effects, throughout the simulation; Subscriber 1 and 2 are free to share their positional estimate in real time with each other. While these limitations may have minimal impact in certain environments, these limitations are likely to affect the simulation accuracy when compared with most real world environments. The accuracy results derived from the model should be considered a 'best case' example.

The case environment to be simulated is that shown in Figure 1. The simulation will assign typical signal generation errors (ETSI 2009) and free space delays to estimate the positional accuracy and confidence level in a multipath environment. The simulation will be broken into two stages. Stage 1, as shown in Figure 2, will simulate the system relying on DRM phase analysis alone. The second stage of the simulation, as shown in Figure 3, will add the layer of system that relies on relative geo-location between subscriber 1 and 2. This will allow the final positional estimate of subscriber 2 to be calculated after combing the uncertainty of subscriber 1 and the uncertainty of the relative position of subscriber 2 from subscriber 1.

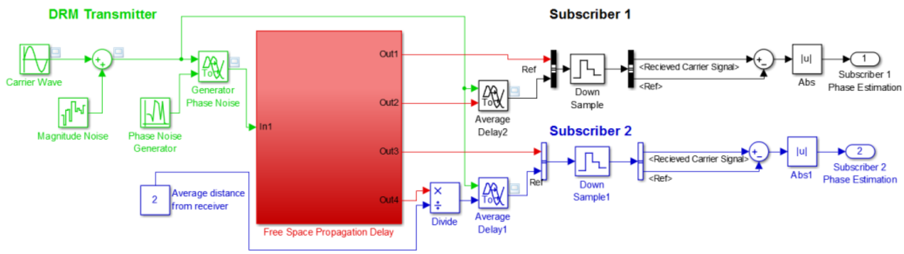

Figure 2: Simulink Simulation of DRM Phase Analysis System

Figure 4 simulates the maximum likely geo-location accuracy of the DRM based system in an area of good RF line of sight to subscriber 1 and while in an area of high multipath, as seen by subscriber 2. The DRM transmitter, comprising of a carrier wave with amplitude and phase noise added is shown in green. The red blocks calculate typical errors of free space transmission in direct path, reflection and refraction environments. The black and blue blocks simulate the receiving and time stamping errors of subscriber 1 and 2 respectively.

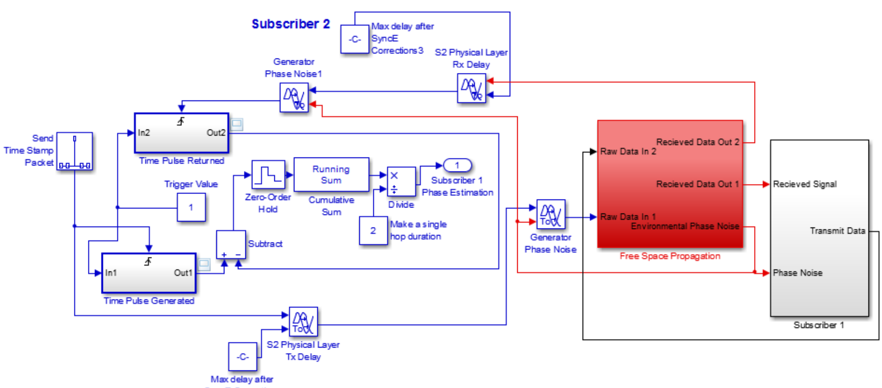

Figure 3: Simulink Simulation of SyncE and PTP Link

Figure 3 shown the simulation model used to estimate the ToA jitter during relative geolocation via a combination of SyncE and PTP. The red blocks simulate typical errors expected from the free space transmission after the corrections applied by SyncE have been applied. The black blocks attribute the reception, processing and transmission errors expected from the subscriber 1 hardware. Subscriber 2, represented by the blue blocks, simulates the appropriate hardware transmission and reception errors of the system. In addition to this, subscriber 2 also monitors the jitter and delay in the system by comparing the difference in the network layer transmission and reception of a pre-determined packet header.

7. Simulation Results

7.1. DRM Phase Analysis

The simulation shown in Figure 2 and Figure 3 was run by Simulink®. The resulting carrier phase analysis noise can be seen in Figure 4.

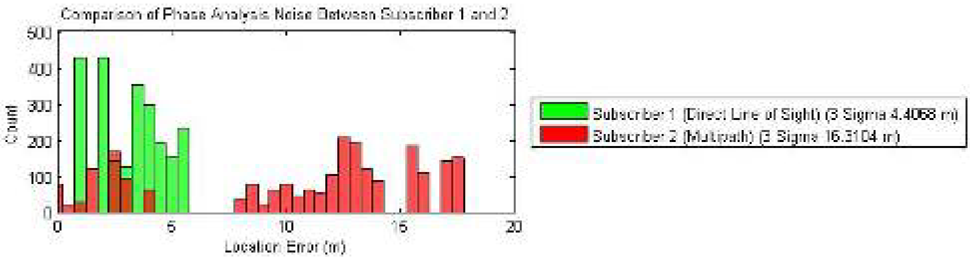

Figure 4: Comparison of Subscriber 1 and Subscriber 2 with DRM Carrier Phase Geo-Location Only

It can be seen in Figure 4 that subscriber 2, the subscriber that is coping with multipath signals, has a significantly wider spread of signal noise. Analysis of the data revealed that the 3σ estimate of position was 4.41 m for subscriber 1 and 16.31 m for subscriber 2.

7.2. PTP and SyncE

The simulation shown in Figure 3 was run. The resulting ToA jitter, causing positional uncertainty in the relative position of subscriber 2 from subscriber 1, can be seen in Figure 5.

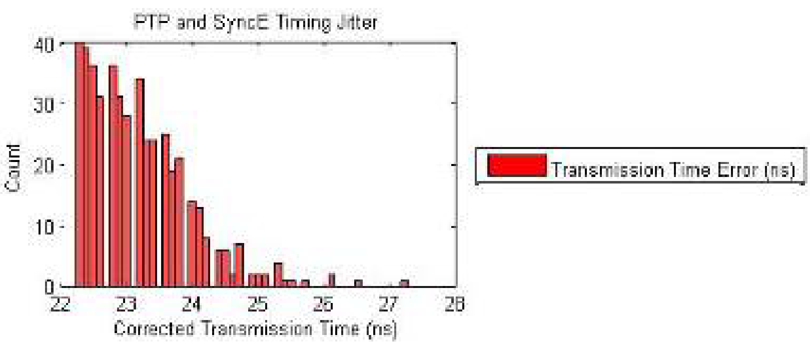

Figure 4: PTP and SyncE Message Timing Jitter

The PTP and SyncE message jitter has been plotted in Figure 4. The 3σ error of the system between subscriber 1 and 2 is 25.489 ns. This equates to a 3σ relative location error of 7.45 m.

As the absolute positional accuracy of subscriber 2 is a combination of the uncertainty of subscriber 1 and the relative position of subscriber 2, the resulting probability density functions (PDFs) have been multiplied together to produce the distribution shown in Figure 6.

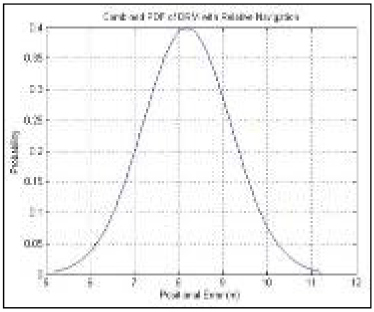

Figure 5: Subscriber 2 Absolute Positional Accuracy

This provides subscriber 2 with a 3σ geo-location accuracy of 10.52 m.

7.3. Summary

Subscriber 1 DRM Geolocation Estimate (3σ) (m)	4.4
Subscriber 2 DRM Geolocation Estimate (3σ) (m)	16.3
Subscriber 2 Combined relative and DRM Geolocation Estimate (3σ) (m)	10.5

Table 1 - Simulation Results Summary

It can be seen in Table that the DRM phase analysis, in the absence of multipath, can provide an order of magnitude improvement over the existing U-TDoA systems used in current E911 systems and could provide the coverage required by NG911 legislation in the simulated environment. In the multipath environment at subscriber 2, the system alone does improve on the existing U-TDoA systems, but is unlikely to provide accurate enough readings for future NG911systems alone.

With the addition of the PTP and SyncE relative geo-location technology, the positional accuracy of subscriber 2 after combining all system uncertainties provides an absolute uncertainty that is significantly better than that found in existing subscriber geo-location systems and may well provide the coverage required by NG911 legislation

8. Future Work

There is potential for the simulation model to be improved by working to remove some of the significant limitations previously highlighted.

9. Conclusion

It has been demonstrated that combining several layers of complimentary geo-location techniques that are either in existence on mature products or emerging from research NG911 geo-location accuracy in dense urban environments could be achieved.

Although each of the technologies used in isolation have significant drawbacks in their ability to provide a geo-location estimate, combining several layers of techniques may allow users to estimate their location in a range of complex environments.

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