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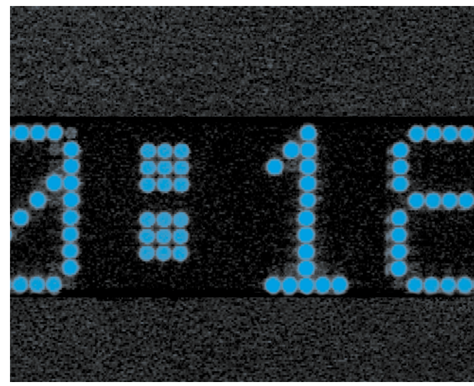
Location of Mobile Handsets – The Role of Synchronization and Location Monitoring Units



WHITE PAPER

Location of Mobile Handsets – The Role of Synchronization and Location Monitoring Units

Background

The location of mobile handsets has been the subject of much discussion over the past five years. One driving force, regulatory in nature, has been the need to locate subscribers who dial in for emergency services (E-911). Many services have been proposed that are location based, and these provide a commercial driving force as well. One such service involves lower rates when the mobile handset is within a designated "home" area, allowing cellular service to compete with landline telephony. Other services proposed include location-based "yellow pages" and selective destinations for 800 numbers.

The importance of obtaining a location fix needs no further discussion. However, the role of synchronization in location finding systems is poorly understood and it is the intent of this paper to provide an appreciation of the need for synchronization for providing robust, accurate, location estimates. The role of a Location Measurement Unit (LMU) is also described.

It will become clear that:

For a robust Location System, the time-base of all the elements of the Location System, including the LMUs and BTSs, must be tightly controlled. This is only possible if all the elements are locked to a high-precision/high-accuracy synchronization source (such as GPS) with adequate holdover performance to bridge outages.

Methods for Location

The most rudimentary of location estimates is the "closest" base transceiver station (BTS) to the handset, sometimes referred to as the Cell-ID method. The received signal powers at the different BTSs which monitor the transmission from the handset, are compared to determine the closest BTS. Often, the location estimate can be improved/enhanced if the BTS uses sectored antennas. This estimate is exceedingly coarse and, though useful in few cases, is woefully inadequate for E-911 and most other applications.

A second methodology is to use traditional location finding equipment, such as GPS (Global Positioning System) receiver chip-sets, embedded into the mobile handset. Whereas this approach has its advantages, we shall consider methods that use the radio signals associated with the cellular telephony system itself for establishing position.

All location finding methods that provide reasonable accuracy are based on *triangulation* (or *trilateration*). The distance between the handset and a BTS is established by estimating the time of transmission between the two points. Based on the distance between the handset and multiple BTSs, the locations of which are known *a priori,* the latitude/longitude of the handset is obtained via the solution of a set of simultaneous non-linear equations. Obtaining the absolute time of transmission may be difficult but it can be shown that the *difference* in transmission time between the mobile and BTSs, taken in pairs, suffices for the purpose of location computation. The accuracy of the location fix is, therefore, directly related to the accuracy with which the time of transmission, or differential time of transmission, can be measured (see Figure 1).

Two distinct approaches for estimating this differential time of transmission are feasible. One approach uses the *up-link* signal, or the signal transmitted by the handset. The other approach uses the *down-link* signal, or the signal(s) transmitted by the BTS(s).

Consider the case where the times-of-arrival (TOA) of the signals from the various BTSs (down-link signals) are measured at the handset using one of the BTSs as the reference. Thus the handset makes an observed time difference (OTD) measurement directly. This OTD measurement is representative of the time difference of *reception* at the handset. In order to establish the time difference of transmission, this OTD measurement is insufficient; the time difference of emission must be measured as well. Conventional handsets make a rudimentary OTD measurement to facilitate smooth hand-overs. However, for hand-over purposes the accuracy and precision required are not very stringent. For use in a Location System, an Enhanced-OTD (E-OTD) measurement is required where "enhanced" implies greater accuracy and precision.

The E-OTD method is currently used with GSM and GPRS network location systems. In these systems, if all the BTSs are synchronized and have a common (time and frequency) reference, the time difference of emission is predetermined and thus known *a priori,* making it relatively easy to determine accurate location. Otherwise, the time-of-emission must be measured against a single reference.

This measurement is the role of the LMU in this scenario. One LMU, appropriately deployed, can serve to make time-of-emission measurements for a cluster of BTSs (see Figure 2). In the other case, the time-of-arrival (TOA)

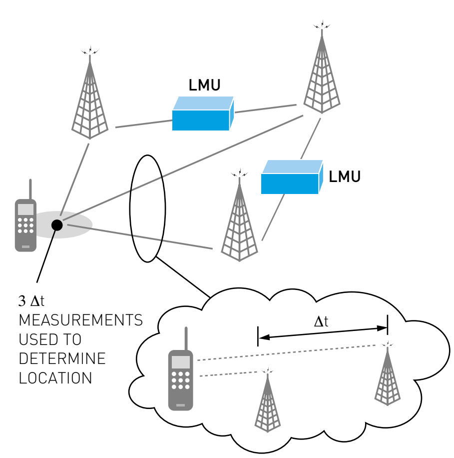


FIG.1 Handset - Time Arrival

of the handset's transmitted signal (the up-link signal) is measured at the BTSs or their surrogates. These TOA measurements are made with respect to a common reference available at all the BTSs, such as a time reference available via GPS. The difference in transmission time is easily computed. Note that a fundamental requirement is that all BTSs (or surrogates) have a common reference (time and frequency) for measuring time-of-arrival. We coin the term OTDOA, for observed time difference of arrival, to describe this approach (up-link measurement). Newly emerging 3G networks of the WCDMA standard use OTDOA to calculate location. Furthermore, the BTSs (also known as Node Bs in WCDMA networks) may not be equipped to make a time-of-arrival measurement for a handset for which it is not the serving BTS at the time (i.e. it is not involved with the call in progress).

The role of an LMU in this scenario may be taken over by timing equipment co-located within the Node B that make TOA measurements for designated handsets. Typically, there will be one timing device for each Node B unless accurate timing can be derived from the Radio Network Controller (RNC) (see Figure 3). Of course, one can conceive of an overlay network, solely for mobile positioning which consists of multiple LMUs deployed to cover the desired service area. The Node Bs would still provide telephony.

The Role of Synchronization

For specificity, we shall first consider the E-OTD approach in the following discussion. The role of synchronization will be evident. Furthermore, it will be evident that synchronization plays the same role in E-OTD and OTDOA scenarios though the function of the LMU is somewhat different in the two cases.

The location of a handset can be computed if the propagation time between the handset and three BTSs can be estimated. In a cellular telephony environment, the mobile monitors signals from other BTSs within the range of its receiver in addition to the BTS it is in communication with. This is necessary to facilitate hand-overs. In particular, the handset can measure the time difference between the "start-of-frame" events of all other BTS receptions relative to the (primary) BTS. This time difference, together with the measurement of the (absolute) "start-of-frame", measured at the BS antenna for each BTS, can be used to establish the difference in propagation time between the mobile and each pair of BTSs. A minimum of two such estimates is required to fix the position (two-dimensional) of the handset.

The notion of "start-of-frame" is simply the time epoch of transmission of a particular pattern that is easily recognizable and is periodic. In GSM, the *Synchronization Burst* contains a 64-bit extended training sequence, the start of which can serve as the requisite time epoch. In the case of CDMA, the first chip of the pilot sequence serves the same purpose. Generally speaking, in terms of a digital (logic) signal, the notion of start-of-frame is intuitive. For example, the rising clock edge that clocks the first bit of the first time-slot of a frame is a logical definition of start-of-frame. However, when the bit-stream is modulated onto a carrier using GMSK and subsequently bandlimited to 200 kHz, as is the case in GSM, the notion of start-of-frame can become somewhat blurred. Nevertheless, it is clear that any **consistent** definition will suffice. As long as each measurement device chooses the **same event** for measurement with respect to GPS-1-PPS (which is a suitable reference), and this event repeats periodically, we can consider that event to be equivalent to a start-of-frame.

The principle underlying the estimation of the difference in propagation time, ΔP_{12}, between a mobile and two BTSs, referred to as BTS#1 and BTS#2, is depicted in Fig. 4. The mobile makes the measurement $(T_3 - T_4)$, which is the time difference between the "start-of-frame" markers for the two BTS transmitters as received at the mobile. Separate equipment, namely the LMU, nominally at each BTS (i.e. cell site), is used to measure the "start-of-frame" with respect to a common reference such as GPS. Denote these measurements by T_1 and T_2 for BTS#1 and BTS#2 respectively. Then:

$$\Delta P_{12} = (T_3 - T_4) - (T_1 - T_2) \qquad (1)$$

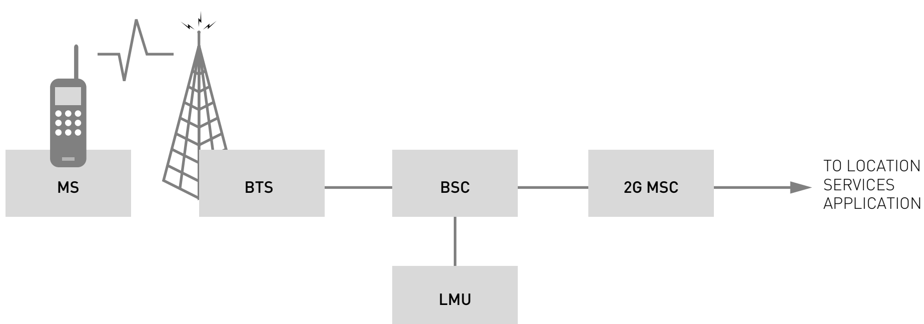


FIG.2 Basic Location System Elements of GSM/GPRS Networks

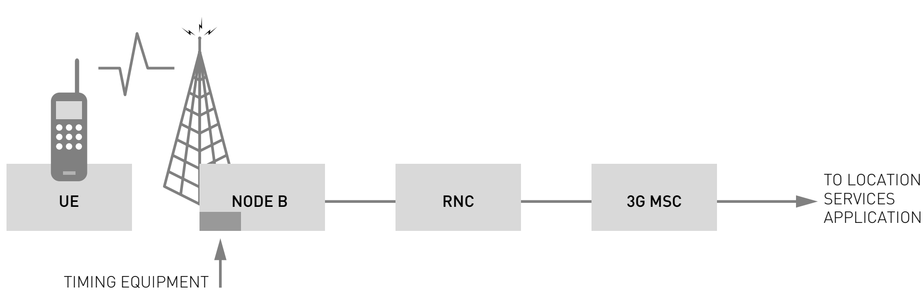


FIG.3 Basic Location System Elements in WCDMA Networks

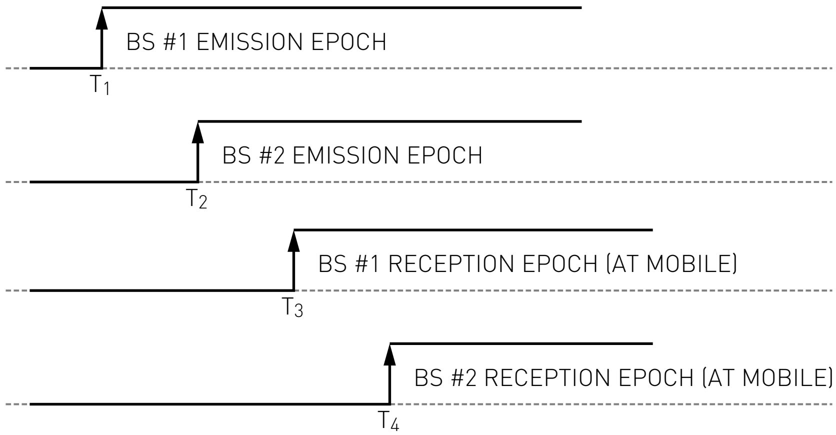


FIG.4 Time epochs of transmission and reception

The accuracy of this estimate is directly related to the accuracy of the position fix. Since time differences translate to position differences via the relationship 1 microsecond ~ 300 meters (the speed of light) a measurement error of 1 microsecond will translate into a position fix error of approximately 300 meters. Actually, if one includes a GDOP (Geometric Dilution of Precision) factor of 3, the position fix error could be almost 1 km. Thus our inability to measure T_1,T_2 and (T_3 - T_4) can be expressed in terms of a positional fix error. In particular, if 100 nanoseconds (rms) is the error budget for the estimation of (T_1 - T_2), the actual measurement of frame emission time must be accurate to 71 nanoseconds (rms) at each BTS location (with respect to an ideal reference) or 100 nanoseconds (rms) at the (shared) LMU (differential).

Consider the situation where a LMU is dedicated to each BTS for the purpose of establishing the emission time. All the LMUs involved in a location fix must have a common reference and GPS (actually the 1-PPS derived from GPS) is a logical choice. The LMU associated with BTS#1 will measure T_1, and the LMU associated with BTS#2 will measure T_2. Even if the measurement process is perfectly accurate, an error can be introduced if the derived reference is erroneous. If we denote by x_1 and x_2 the rms (root-mean-square) errors in the derived references, the resultant rms error in the computed quantity (T_1 - T_2) can be estimated (assuming the errors are independent) using the following equation:

$$x_{12} = \sqrt{x_1^2 + x_2^2}$$

If we designate the error budget for the computed quantity as 100 nsec, the error budget for each of the derived references (assuming an equal allocation) would be 71 nsec. This tight restriction becomes problematic if the LMU experiences a GPS outage since the holdover requirement would then be 71 nsec over the duration of the outage. Since the measurement process (obtaining T_1 and T_2) may itself be "noisy", the budget allocated to the reference accuracy must be correspondingly reduced. If we allocate an equal error budget to the two references and the two measurement processes, then the individual budget drops to 50 nsec. Clearly, if we designate the error budget for the computed quantity as less than 100 nsec, the individual components have a correspondingly smaller budget.

The situation where an LMU is "shared" is somewhat different. Here one LMU is positioned at a convenient (known) location, monitors the transmissions from both BTSs, and measures the observed time difference in much the same way as the handset does. Needless to say, any inaccuracy introduced in determining the location of the LMU translates directly into an equivalent error in the estimate of (T_1 - T_2). Furthermore, vagaries of radio transmission such as multipath may also introduce errors. However, the notion of absolute time reference is moot since both T_1 and T_2 are measured against the same reference. The error budget can be allocated to the measurement process (and multi-path, LMU location inaccuracy, etc.). The frequency offset of individual BTSs does impact this measurement. If there is a relative frequency difference between the master clocks of BTS#1 and BTS#2 of ***F*** ppb (parts per billion), then measurements of the same quantity, (T_1 - T_2), taken ***R*** seconds apart will differ by as much as ***F.R*** nsec. Clearly, for the Location System to be robust, the frequency difference must be maintained at a low level that can be achieved only if both BTSs (and, to a lesser extent, the LMU) are locked to the same synchronization source (such as GPS).

Whereas the need for accuracy of the time reference required in individual LMUs is quite evident, the role of synchronization in the accuracy of (T_3 - T_4) is somewhat more subtle. It may appear that since the handset will use its (internal) time reference to measure both T_3 and T_4 and thus derive the difference, synchronization is moot. This is untrue. The handset will be using a BTS, say BTS#1, as its "master" and derive its timing therefrom. Now it is more than likely that the handset will monitor BTS transmissions in a "round-robin" manner since such OTD measurements are but an adjunct to the principal function of telephony. Thus a certain period of time, say ***R*** sec., will elapse between the measurements of T_3 and T_4. If BTS#1 and BTS#2 have different time-bases, this interval between measurements can introduce an error. Suppose the master clocks of BTS#1 and BTS#2 are different by 50 ppb (this difference is within the GSM specification). This frequency offset will introduce an error of 50***R*** nsec in the estimate of (T_3 - T_4); a difference of ***F*** ppb will cause an error of as much as ***F.R*** nsec.

A similar discussion applies to the OTDOA scenario. Here the BTS, or surrogate LMU, measures the time-of-arrival of the mobile's transmission. A minimum of three such TOA estimates is required for a two-dimensional location fix. The principle underlying the estimation of the difference in propagation time, ΔP_{12}, between a mobile and the two BTSs, BTS#1 and BTS#2, is depicted in Fig. 5. The LMU, nominally at each BTS (i.e. cell site), is used to measure the time-of-arrival with respect to a common reference such as GPS. Denote these measurements by T_1 and T_2 for BTS#1 and BTS#2 respectively, then:

$$\Delta P_{12} = (T_1 - T_2) \qquad (2)$$

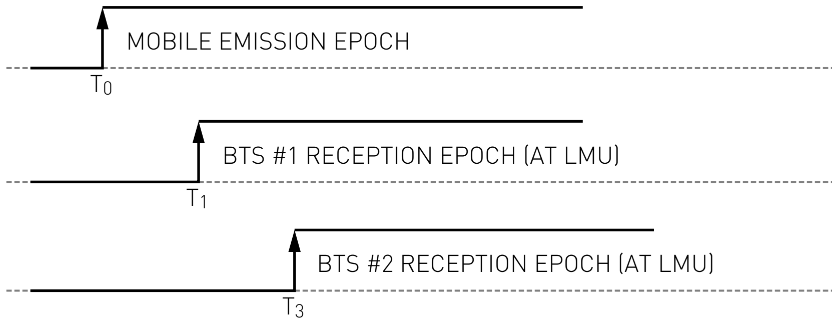


FIG.5 Time epochs of transmission and reception

The analysis of errors introduced because of timing variation closely parallels the E-OTD case. Here too, the LMUs must have equivalent time and frequency references. Since the measurement of time-of-arrival at the two LMUs may be done at different times, and since the mobile uses its serving BTS for timing, it follows that the BTS and LMU(s) must have the same time-base.

Synchronization and Enhancement of Location Accuracy

Each measurement is likely to be inaccurate. This measurement inaccuracy is representative of perturbations from a variety of sources and which are generically classified as "noise". The conventional technique to combat this noise is to make multiple measurements of the same quantity and average the results. If the noise is "random" and is uncorrelated from measurement instance to measurement instance, then averaging does improve the accuracy, reducing the error variance by a factor of N, where N is the number of measurements that comprise the average. Implied in the averaging scheme is that the "true" value is constant from measurement instance to measurement instance.

Needless to say, these measurements are not made simultaneously. Some interval of time will elapse between measurements. An underlying frequency offset of ***F*** ppb will introduce a drift of ***F.R*** nsec if the measurements are made R seconds apart in time. This drift will negate the noise amelioration available via averaging. It is advisable to ensure that this drift effect be substantially less than the error budget allocation for the measurement in question.

Conclusion

For a robust Location System, the time-base of all the elements of the Location System, including the LMUs and BTSs, must be tightly controlled. This is possible only if all the elements are locked to a high-precision/high-accuracy synchronization source (such as GPS).

SYMMETRICOM, INC.
2300 Orchard Parkway
San Jose, California
95131-1017
tel : 408.433.0910
fax : 408.428.7896
info@symmetricom.com
www.symmetricom.com

SYMMETRICOM EMEA
150 Wharfedale Road
Winnersh Triangle, Nr. Wokingham
Berkshire
RG41 5RB, United Kingdom
tel : 44 (0) 1189 699 799
fax : 44 (0) 1189 277 520
info@symmetricom.com

SYMMETRICOM LATIN AMERICA
1560 Sawgrass Corporate Parkway
4th Floor
Sunrise, Florida
33323
tel : 954.331.4592
fax : 954.331.4601
info@symmetricom.com

SYMMETRICOM ASIA PACIFIC
Unit 1005, Jubilee Centre
42–46 Gloucester Road
Wan Chai
Hong Kong
tel : 852.2529.7180
fax : 852.2529.7190
info@symmetricom.com