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Network & Terminal based Wireless Positioning Techniques

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Abstract:*Positioning based services really picked up pace in the early 90's which came with the emergency response lines like 911, 100, etc. and which due public awareness regarding the location services being offered. These services also extend to the transport and logistics side an example of which would be that nowadays taxies have inbuilt location bases services to track the vehicles.*

There are multiple positioning based services available like GPS, GLONASS, Time of Arrival, Angle of Arrival, etc. with each having their own pros and cons.

We shall cover some of these services and review them for their functioning and functionality.

Keywords:GLONASS, Angle of Arrival, Time of Arrival, Timing Advance, Terminal Positioning, Network Positioning, WSN (Wireless Sensor Network), GPS, Geolocation

1. INTRODUCTION

Positioning based services are divided into two basic parts terminal based services and network based services. In this review paper we will be covering one terminal based service namely GLONASS and three network based services namely angle of arrival, time of arrival and timing advance.

GLONASS is a terminal based service which uses satellites launched by the Russian government. It was originally meant for Russian military but it was later released for public use and today it stands with only GPS above it with many leading manufactures providing receivers for both now.

Angle of Arrival is the first of the network based services we will be covering it consists of node which exist in wireless sensor networks. The location is derived using multiple nodes using algorithms and formulas.

Time of Arrival is one of the three network based service .Certain improvements is required in the time domain resolution of the channel response to resolve the multipath and raise up the accuracy of estimation. For time-domain analysis of different applications, the Multiple Signal Classification (MUSIC) algorithm was used, a super resolution technique, which gave better TOA estimation. Classification of channel profiles and the performance analysis gives profound insight into wireless channel modelling for indoor geolocation.

Timing advance is the last of the network based service we will be discussing multiple signal transmissions from receiver to base station and vice versa. It also handles single channeling timing and assigning right time slots. We see the use of two types of methods by which we estimate the base station positioning that are pointmass filter and Gaussian mixture filter.

2. GLONASS

Globalnaya Navigatsionnaya Sputnikovaya Sistema translated to Global Navigation Satellite System and also known as

GLONASS is a Russian Aerospace Defence Force-operated satellite-based navigation system that is very similar and yet different when compared to GPS.

There are 3 things which come together and make GLONASS tick, the first one being the satelliteconstellation itself. These are a group of satellites which are set up in orbital planes/paths around the Earth and they work together with Ground LocationNetworks which is the second component of the system.

The Ground Location Networks augment the speed and accuracy of the satellites by feeding back geodesic information (relating to or denoting the shortest possible line between two points on a sphere or other curved surface). Such networks are placed across the world but the availability the ones compatible with GLONASS is lesser than those compatible with GPS. These networks then triangulate the position device.

The device being the third component, it is any mobile, navigation system that is compatible with GLONASS.

The satellites send out signals at precise intervals, using the contents of these signals triangulation is performed using a series of calculations. For a device to position itself, it needs the signal from 4 or more satellites which in turn give the position and velocity of the device.[1]

Position:

$$x_a(t_e) = x(t_e)\cos(\theta_{G_e}) - y(t_e)\sin(\theta_{G_e})$$

$$y_a(t_e) = x(t_e)\sin(\theta_{G_e}) + y(t_e)\cos(\theta_{G_e})$$

$$z_a(t_e) = z(t_e)$$

Velocity:

$$v_{x_a}(t_e) = v_x(t_e)\cos(\theta_{G_e}) - v_y(t_e)\sin(\theta_{G_e}) - \omega_E y_a(t_e)$$

$$v_{y_a}(t_e) = v_x(t_e)\sin(\theta_{G_e}) + v_y(t_e)\cos(\theta_{G_e}) + \omega_E x_a(t_e)$$

$$v_{z_a}(t_e) = v_z(t_e)$$

The $(X''(t_e), Y''(t_e), Z''(t_e))$ acceleration components broadcast in the navigation message are the projections of luni-solar accelerations to axes of the ECEF Greenwich coordinate system. Thence, these accelerations must be transformed to the inertial system by:

$$(Jx_a m + Jx_a s) = (X''(t_e)\cos(\theta_{G_e}) - Y''(t_e)\sin(\theta_{G_e}))$$

$$(Jx_a m + Jx_a s) = X''(t_e)\sin(\theta_{G_e}) + Y''(t_e)\cos(\theta_{G_e})$$

$$(Jx_a m + Jx_a s) ='' (t_e)$$

Where (θ_{G_e}) is the sidereal time at epocht_e, to which are referred the initial conditions, in Greenwich meridian:

$$\theta_{G_e} = \theta_{G_0} + \omega_E(t_e - 3\ hours$$

Being:

ω_E: Earth's rotation rate ($0.729211510^{-4} rad/s$).

θ_{G_0}: The sidereal time in Greenwich at midnight GMT of a date at which the epoch t_e is specified. (Notice: GLONASS time = UTC (SU) + 3 hours).

GLONASS receivers are both larger and expensive due to the fact that the support both FDMA and CDMA in comparison to GPS receivers as they do not support FDMA. In order to allowcompatibility with GPS satellites, GLONASS has been using CDMA since 2008.

GLONASS's satellite constellation consists of a total of 3 orbits which areseparated by 120°, each orbit consists of 8 satellites which are evenly spaced from each other. At the other hand, GPS has 6 orbits spaced at 60° and each orbit consists of 4 satellites which are unevenly spaced. Both systems need 24 satellites to remain operational, currently GPS has 31 active satellites were as GLONASS only has 24. Lower number of active satellites combined with fewer ground location networks leads to reduced accuracy and increased time for establishment of connection for a device that depends only on GLONASS.

Under the best environment i.e. no cloud coverage, tall buildings or radio interference GLONASS is accurate up to 2.8 meters, averaging at 5 to 10 meters under normal conditions, which is only slightly less than the accuracy of GPS, 3.5-7.8 meters. GLONASS is also more accurate in the northern hemisphere than the southern due to the fact that there are more ground location networks that support GLONASS present there.

But the biggest difference between the two lies in the way they communicate with receivers. GPS uses the same radio frequency but has different communication codes whereas in the case of GLONASS, the satellites share the same code but use unique frequencies.

Nowadays, most manufacturers include both GPS and GLONASS chips in their devices, but neither is it as widely provided by manufactures nor is it exclusively used by users. Although in unfavorable conditions, a device that is having difficulty in either establishing connection or in getting an accurate reading of location, both GPS and GLONASS are used in conjunction. This allows the device to be able to be pinpointed by any of the 55 satellites orbiting the Earth which in turn increases overall accuracy and decreases the time required to acquire satellites by up to 20%.

3. ANGLE OF ARRIVAL

Nowadays, wireless sensor networks (WSNs) attract a lot of attention from the telecommunication world. Monitoring an environment in dangerous regions, controlling an inventory in storehouses[2],tracking patients in hospitals or monitoring enemyforces in a battlefield are only someof the countless possible applications of it. Data gathered by sensor nodes is only useful if we can attach the position of the node along with the data and it is worthless without it. Thus, it is crucial that sensor nodes know their positions with the aid of a localization algorithm.

A well accepted approach upon the problem of localization still does not exist due to the existence of large number of nodes supported by their low cost, mounting a GPS receiver at each node is not feasible. There have been a large number of localization techniques proposed so far such as time-of-flight, time difference of arrival and angle of arrival.

The idea behind AOA (angle of arrival) localization system is that directional antennas are attached to some sensor nodes, these nodes are then developed and carefully analyzed. The network is then configured such that multiple hops are required for the communication between the sensor nodes and the base stations.

Beacons are nodes that are always aware of their position as they are either equipped with a GPS receiver or they are hand placed keeping the position in mind. The remaining nodes do not know their position and are referred to as unknowns and use the beacons position to localize themselves.

AOA is not only useful in tracking a given signal but also for improving the signal reception for movable users. With the AOA detection, the beam pattern of the antenna system can be reconfigured either mechanically or electrically to improve the signal reception.

AOA is the angle between the incident wave's propagation direction and a reference direction, orientation which is a fixed direction against which the AOAs are measured. It is represented in degrees and is measured in a clockwise direction from the North. When the orientation is 0° that is, it is pointing to the North, AOA is absolute, otherwise, relative. Using an antenna array on each sensor node is a common way to obtain AOA.

The orientations of the unknowns may or may not be known. Localization under both scenarios is done using triangulation.

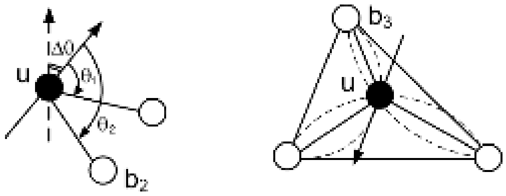

Fig 1: Triangulation in AOA localization:

(a)Localization with orientation information; (b) Localization without orientation information.

In Fig. 1(a), θ_1 and θ_2 are angles measured at unknown u, that are relative AOAs of the signals sent from beacons b1 and b2, respectively. Assuming $\Delta\theta$ as the orientation of the unknown, the absolute AOAs from beacons b1 and b2 can be calculated as

$(\theta_i + \Delta\theta)(\mathrm{Mod}\ 2\pi),\ i = \{1, 2\}$.

Experimental results are mentioned in paper[13] each absolute AOA measurement corresponding to a beacon restricts the location of the unknown along a ray starting at the beacon. At the intersection of all rays when two or more non-collinear beacons are available is the location of the unknown u. When the absolute AOAs cannot be obtained i.e., the orientations of the unknowns are not available, the AOA differences are used instead[3]. In Fig. 1(b), angles:

$\angle b1ub2$, $\angle b1ub3$ and $\angle b2ub3$ can be computed using the knowledge of the relative AOAs. All angles subtended by the same chord are equal. Thus, given 2 points and the chord joining them together, a third point from which the chord subtends a fixed angle is constrained to an arc of a circle. For example, the angle $\angle b1ub2$ and the chord b1b2 restrict u's position on the arc passing through b1, u and b2. Since each chord determines one arc, intersection of all arcs when three or more non-collinear beacons are available is the location of the unknown.

At least two non-collinear neighbor beacons along with orientations are required to discover the location, and at least three to discover both the location and the orientation. All this is then further calculated using the help of formulas and algorithms.

4. TIME OF ARRIVAL

4.1. Classification based on physical characteristics

Channel profiles measured in different locations of a buildingare divided intoLOS (Line Of Sight) and OLOS (Obstructed Line Of Sight) .When the transmitter and receiver have no physical obstructions between them the measurement it is referred to as LOS. When an obstruction exists, such as a wall, the profile is referred to as OLOS.

4.2. Classification based on measurement characteristics

The measurement is classified according to the power and the availability of the TOA of the DLOS (Direct Line Of Sight) path[4]. To establish whether the DLOS path is detected or not, a threshold was used. When the first path is above the threshold but gets weaker, the profile fits in the NDDP (Non Dominant Direct Path) category. A more complex rake receiver can be used to resolve the multipath and detect the TOA of the DLOS path, leading to an overall reduction in loss of accuracy.Overall UDP (Undetected Direct Path) is expected to show strong degradation in TOA estimation for geolocation application compared with the other scenarios.

4.3. UDP Challenge

A major error contributor, UDP is the most significant hurdle to the accuracy of indoor geolocation systems. In most of the cases, UDP is caused by the existence of a metallic obstruction in the direct path. In other cases, there may be a number of walls that attenuate the first path compared to the other paths. In both the cases, the paths arriving from different directions are much stronger. When analyzing the performance of an indoor geolocation system, it is important to have an in-depth assessment on why and where this UDP happen so that it can shed light on how to avoid it. When it is inevitable, there are ways to resolve it - o to use estimation algorithms to try to resolve the multipath and reduce the error in UDP conditions and the other might be in view of the bandwidth of the system

5. TOA ESTIMATION ALGORITHMS

IFT (Inverse Fourier Transform)gives a time domainrepresentation of the channel profile from the frequency domain measurement data. When the time domain response over part of the time period is required, the chirp-z transform (CZT) is preferred, providing flexibility in the choice of time domain parameters with the cost of longer computational time as compared with the IFT. The term IFT mean application of the CZT unless otherwise stated.

DSSS (Direct Sequence Spread Spectrum)simulates DSSS signal-based cross-correlation technique, the frequency response of a raised-cosine pulse with roll-off factor 0.25.It is first applied to the frequency domain response as a combined response of band-limitation pulse-shaping filters of the transmitter and receiver. Then, the resultant frequency response is converted to time domain using the IFT for TOA estimation.

5.2. Super resolution [EV/Forward-Backward Correlation Matrix (FBCM)]

A variant of MUSIC algorithm is used as a super-resolution technique in TOA estimation[5]. The indoor radio channel suffers from severe multipath. The equivalent low pass impulse response is given by

$$h(t) = \sum_{k=0}^{L_p-1} (\alpha_k \delta(t - \tau_k)$$

Where L_p is the number of multipath components is

$$\alpha_k = |\alpha_k| e^{j\theta_k} and \tau_k$$

Are the propagation delay and complex attenuation of the $\mathbf{k}^{th}$ path. The frequency domain channel response i.e., the Fourier transform of the above equation is given by

$$H(f) = f(x) = a_0 + \sum_{k=0}^{L_p-1} (\alpha_k)$$

A harmonic signal model can be created by exchanging the role of frequency and timing variables in which yields,

$$H(\tau) = \sum_{k=0}^{L_p-1} \alpha_k e^{-j2\pi f_k \tau}$$

This model is very well known in spectral estimation field[6]. In this paper, a variant of MUSIC algorithm is used as a spectral estimation technique to get the time domain profile from the frequency domain data for determining the TOA and DLOS path. The channel frequency response H (f) at L are sampled at equally spaced frequencies to obtain the discrete measurement data. Considering additive white noise in the measurement, the sampled discrete frequency domain channel response is given by

$$X(l) = H(f_1) + w(l)$$

$$= \sum_{k=0}^{L} \left(\alpha_k e^{-j2\pi(f_0 + l\Delta f)\tau_k}\right) + w$$

Where l= 0, 1,..., L-1 and w (l) denotes additive white measurement noise with zero mean and variance$(\sigma_w)^2$. The signal model in vector form is

$$x = H + w = Va + w$$

Where V=$\left(v(\tau_0)\ v(\tau_1) \ldots v(\tau_{L_p} - 1)\right)^T$, and V =$\left(1e^{-j2\pi\Delta f\tau k} \ldots e^{-j2\pi(L-1)\Delta f\tau k}\right)^T$. The L-dimensional subspace that contains signal vector x is split into two orthogonal subspaces, which are known as signal subspace and noise subspace, by the signal EVs(Eigenvector) and noise EVs, respectively. Since vector v(τ_k), 0 ≤ k ≤ $L_p - 1 \mathbf{mustlieinthesigalsubspace}$.

$$P_w v(\tau_k) = 0$$

Where P_wv (τ_k) is the projection matrix of the noise subspace.

$$S_{MUSIC}(\tau) = \frac{1}{(||P_w v(\tau)||)^2}$$

$$= \frac{1}{\sum_{k=L_p}^{L-1} (|q_k v(\tau)|)^2}$$

Where q_k are the noise EVs. The pseudospectrum is defined as

$$S_{EV}(\tau) = \frac{1}{\sum_{k=L_p}^{L-1} \frac{1}{\lambda_k} |q_w^H v(\tau)|^2}$$

There λ_k , $L_p \leq k \leq L - 1$ are the noise eigenvalues. EV/FBCM (Eigenvector/Forward Backward Correlation Matrix) refers to the type of MUSIC algorithm that is applied throughout this paper, unless otherwise stated.

6. TIMING ADVANCE

TA is a kind of Round Trip Time (RTT) from mobile phone to BS (Base Station).It is used to minimize interference in Time-Division Multiple Access systems (TDMA)[7].When multiple mobile phones are sending on the same physical channel they need to know the right time to send the signal so that data arrives to BS antenna on the right timeslot. The mobile phone and BS do initial synchronizationon Random Access Channel (RACH) using zerotiming advance. Now the base station tells the mobile phone how much transmission has to be advanced. Granularity of TA is a GSM bit (48/13μs).TA is not always available in mobile phone for e.g., when the radio link is in idle-state then TA is not available. TA measurement may be transformed to a discrete distance measurement with granularity of:

$\Delta TA = c \cdot 24/13\mu s \approx 550m$. (Since One round trip is of 1100m).

A.

6.1. Ideal Model

The discrete TA measurement presented above may be also written as

TA= Floor $[\frac{[\|XM - xBS\|]}{d_{ta}}]$

Where X_m is the position of the mobile phone and X_{bs} is the BS position. Here xm is computed through mobile phones GNSS.

For ideal TA measurement

$P(TA|X) = \{1, 0 <= \|X_m - X_{bs}\| - TAdTA < dTA\}$

$\{\ \ 0, \text{Otherwise}\}$

Two different methods for estimating BS position are presented in the following section. The first method is Point Mass Filter (PMF)[8, 9] that is quite simple and converges to the exact posterior distribution as the number of computation points increases. The second method is GMF (Gaussian Mixture Filter)[10, 11] that estimates the probability distribution using multiple Gaussians and is faster than PMF[12]. Both of these filters, PMF and GMF are Bayesian filters, whose aim is to compute posterior distribution of the BS position p (xBS|TA1: n), given all available TA measurements TA1: n= {TA1, TA2,…, TAn}. We assume:

- TA measurements are conditionally independent given the XBS

- BS position is static

The initial prior distribution p

$\boldsymbol{p}\ (\boldsymbol{x_{t0}^{BS}}|$ TA 1:0) = p $(\boldsymbol{x_{t0}^{BS}})$ is uniform.

- Local 2D coordinate system is used.

- First measurement is at the origin of the coordinate system.

- Each measurement position has zero error i.e. position error has been incorporated into the TA measurement model.

To calculate positioning of base station Gaussian Mixture Filter is used.

6.2 Initialization of GMF

The initialization is done using the first TA measurement. The idea is to compute Gaussian mixture approximation of the posterior distribution at time t1. Since the initial prior distribution is uniform, we can compute Gaussian mixture approximation of the first likelihood function p (TA1|xBS). In this case we use

$M\ (\alpha_{j,\ 1,\ \mu j,\ 1,\ Pj,\ 1})_{(j,\ N)}$

Where
$\alpha = 1/N_{GMF,\ 1}$
$\mu = Q_{j.} \int_A x^{BS}\ p\ (TA_1|x^{BS})\ dx^{BS} / \int_A p\ (TA1|x^{BS})\ dx^{BS} \approx Q_j\ \{\mu_{ta,}$ 0}

Pj,1=

$$Qj\ \frac{[\int \mathbf{A}(x^{BS} - \mu_{j,1})(\mathbf{x} - \mu_{j,1})^T\ .\mathbf{p}(\mathbf{TA_1}|\mathbf{x}^{BS})\mathbf{dx}^{BS}}{\int \mathbf{A.p}(\mathbf{TA_1}|\mathbf{x}^{BS})]\ \mathbf{dx}^{BS}}$$

$$Q\ j = [\cos\ (\frac{\mathbf{2\Pi j}}{\mathbf{NGMF\ ,1}}).\sin\frac{\mathbf{2\Pi j}}{\mathbf{NGMF\ ,1}}]$$

$$-\sin\ (\frac{\mathbf{2\Pi j}}{\mathbf{NGMF\ ,1}}\cos\frac{\mathbf{2\Pi j}}{\mathbf{NGMF\ ,1}}]$$

$$A = [\boldsymbol{x}.\frac{\boldsymbol{x1}}{\boldsymbol{x}} \geq \mathbf{cos}(\frac{\boldsymbol{\Pi}}{\boldsymbol{Ngmf}})]$$

6.3 Update

$\mu = h\ j\ (xBS) + v\ j = \|\ xBS + xM\| + v\ j$, where $v \sim N\ (0, \sigma 2ta)$,

Now if we see the posterior approximation which says occurrence of

$$\boldsymbol{M}(\boldsymbol{\alpha_j^+}, \boldsymbol{\mu_j^+}, \boldsymbol{P_j^+})_{(j, N_{GMF^+})},$$

$$\boldsymbol{H_{j=}} \begin{cases} \dfrac{(\boldsymbol{\mu_j^-} - \boldsymbol{x^M})^T}{\|\boldsymbol{\mu_j^-} - \boldsymbol{x^M}\|}, \boldsymbol{if}\|\boldsymbol{\mu_j^-} - \boldsymbol{x^M}\| \neq \mathbf{0} \\ [\mathbf{00}],\ \ \boldsymbol{otherwise} \end{cases}$$

$$K_{j=\frac{1}{H_j P_j^- H_j^T} P_j^- H_j^T}$$

$$\alpha_j^+ \propto \alpha_j^- e^{-\frac{(\mu_{ta_j}-h_j(\mu_j^-))^2}{2(H_j P_j^- H_j^T + \sigma_{ta_j}^2}}$$

$$\mu_j^+ = \mu_j^- + K_j(\mu_{ta_j} - h_j(\mu_j^-))$$

$$P_j^+ = (I - K_j H_j) P_j^-$$

6.4 Reduce the number of components:

Components are reduced using two different methods[13,14,15]. In the first method, components having a weight α j + less than some threshold are simplydropped and the weights of the other components arerenormalized. In thesecond method components are merged, if they are close to each other i.e. $\|\mu_i^+ - \mu_j^+\| < \theta$ where θ is the component merge distance. The parameters for the new merged component may be written as follow

$$\mu_l = \frac{\alpha_i^+ \mu_i^+ + \alpha_j^+ \mu_j^+}{\alpha_i^+ + \alpha_j^+} 14.30.$$

$$P_l = \frac{\alpha_i^+}{\alpha_i^+ + \alpha_j^+}[P_i^+ + (\mu_i^+ + \mu_l)(\mu_i^+ + \mu_l)^T] + \frac{\alpha_j^+}{\alpha_i^+ + \alpha_j^+}\left[P_j^+ + (\mu_j^+ + \mu_l)(\mu_j^+ + \mu_l)^T\right]$$

$$\alpha_l = \alpha_i^+ + \alpha_j^+$$

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