Relative Navigation for Node of Wireless Decentralized Network

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Abstract. The problem of determining the geographical coordinates of the wireless unit in the presence of a decentralized network of airborne navigation receivers on some other sites is researched. Similar solutions for locating a subscriber to GSM is considered, its shortcomings is revealed. A mathematical apparatus for the relative navigation based on multilateration is offered. An experiment to determine the geographic origin and the comparison of its results with the calculated data is carried. Considerations to restrict the mobility of nodes in different variants of the construction of the network is formulated.

Keywords: Navigation · Geographical coordinates · The wireless network

1 Introduction

The development of wireless transmission is a rapid pace [1], along with the navigation problem put their subscribers. In case of failure or absence of GPS signals, or in areas without GSM coverage, or to improve positioning accuracy relative navigation becomes necessary. This is especially true for decentralized networks [2,3], when the nodes are mobile and move in space, such as sensor networks or operative networks of tablet computers in places of emergencies [4].

There are two main methods for relative navigation subscriber in the network GSM [5] method of obtaining the time (Time of Arrival – TOA); time difference method (Enhanced Observed Time Difference, EOTD). The method of obtaining the time (TOA) [6] similar to the GPS satellite navigation technology and is based on the measurement of the delay in the shift of the frame with the signal from the base station to the phone where the distance to the base station. To determine the coordinates should be at least three simultaneous bearing. Calculations made by the operator of the triangulation algorithms. The time difference method (EOTD) [7] measured delay time difference signals from the two closest base stations, which is then converted to distance. Feature EOTD method is

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the need to integrate the mobile terminal computing module, which also passed the exact coordinates of the base stations, so blocks LMU base stations requires several times less than the TOA. EOTD has spread in networks with CDMA technology and is supported by some models of terminals to networks GSM. According to some estimates, the accuracy of the method EOTD exceed TOA.

The disadvantage of these methods is the high accuracy of determining the coordinates in a big city it is usually up to 400 m, in the regional center to a kilometer in rural areas and along the routes of 15–20 km. In addition, both methods require the installation of base stations LMU special module for calculating position places. The methods are applicable only in the area of GSM coverage.

Also known relative navigation method based on measurement of received signal power [8,9]. In the method of approximation conducted a distant relation of the type $\frac{1}{r^n}$ characteristics, where $n > 2$. This takes into account attenuation when passing the road and heterogeneity of the antenna pattern. This method is not tied to coverage GSM, but, despite the simplicity of calculations obtained by averaging feature provides low accuracy location.

A method of relative navigation unit wireless decentralized network based on measurements of the received signal power from a distant approximation characteristics dependent species $\frac{1}{r^2}$ and taking into account the position error.

2 Theoretical Basis of Relative Navigation

Block diagram of the geographic coordinate data from several nodes at the same time still represented in Fig. 1, one movable at different points in time (b) and distant feature (c).

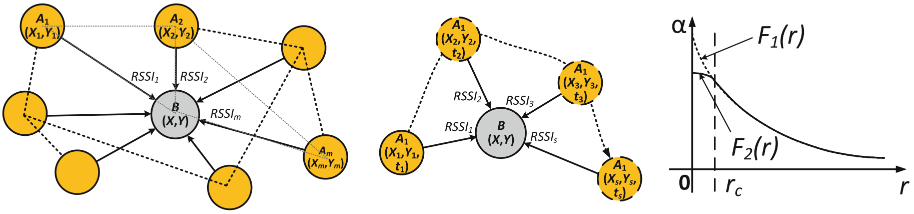


Fig. 1. Scheme geographical coordinate data from multiple fixed units (a), one movable (b) and distant characteristic (c)

In the case of (a), components $A_1, \ldots, A_m$ (beacons) with navigation data $(x_1, y_1), \ldots, (x_m, y_m)$, send your coordinates broadcast packets node B (locator) with coordinates (x, y) that has no navigation data, and calculates the levels of signals $RSSI_1, \ldots, RSSI_m$ [8]. In the case of (b) node A_1 (beacon) is moved on the plane and at times $t_1, \ldots, t_s$ sends its coordinates $(x_1, y_1), \ldots, (x_s, y_s)$ fixed node B (locator), which calculates the coordinates (x, y) of the signal levels

$RSSI_1, \ldots, RSSI_s$. It is also possible combined variant relative navigation event (a) with mobile nodes in the case (b), which increases the quality of the calculated data.

Thus, initial data for relative navigation coordinates are other network nodes (at least 2) and the ratio $RSSI$ of the received signal power level. Location determined by multilateration and methods of passive radar. It is necessary to take into account the dependence of the signal power of the distance (a distant characteristic), the presence or absence of obstacles in the signal path and the error location.

On the strength of the received signal is influenced by:

(a) the projective ("radiant") weakening;
(b) reflection and refraction (obstacles — terrain, buildings, structures, etc.);
(c) interference, diffraction, etc. (challenging obstacle and so forth.);
(d) the relative orientation of the transmitting and receiving antennas;
(e) absorption (rain, fog, smog, etc.).

Factor (a) the most dominant. As you know, in the free space capacity of the received electromagnetic wave from a point source is inversely proportional to the square of the distance from the source (Friis formula):

$$P^R = P(r) = P^T G^R G^T \Big(\frac{\lambda}{4\pi r}\Big)^2, \quad r > 0, \tag{1}$$

where r — the distance between the beacon and locator, P^T — power signal emitted by the antenna of the transmitter (beacon), P^R — the signal strength received by the antenna receiver (locator), G^T and G^R — gains of transmitting and receiving antennas, respectively, λ — the wavelength. We denote further $\alpha := P^R/P^T = u(P^R, P^T)$, $\beta := 10 \lg \alpha = RSSI = \nu(P^R, P^T)$ — the relative power of the received signal according to the linear and logarithmic scale, respectively. Then we get:

$$\alpha = F_1(r) = K_1/r^2, \quad r > 0, \tag{2}$$
$$\beta = 10 \lg(K_1/r^2) = K_2 - 20 \lg r, \quad r > 0, \tag{3}$$

where F_1 — a distant point source characteristics. Parameters link

$$K_1 = G^R G^T \Big(\frac{\lambda}{4\pi}\Big)^2 \text{and } K_2 = 10 \lg K_1 \tag{4}$$

It can be considered permanent.

If the radiator — not a point but a small body (antenna), the pole at the $r = 0$ point is smoothed (near field), but far enough away from the body (far-field) can be regarded as a point and the "inverse square law" would be applied. It can be approximated by a distant features as follows:

$$\alpha = F_2(r) = K_1 \Big(\exp(-ar^2) + \frac{1}{r^2} \exp(-b/r^2)\Big), \quad r > 0, \tag{5}$$

where F_2 — distant antenna characteristics.

Since $F_2(r) \approx F_1(r)$ for $r \geq r_c$ the conventional boundary near and far zones antenna (Fig. 1c), and near-field problems locating antennas are not used, it is possible to restrict the formula (1) for $r \geq r_c$. Furthermore, if the transmitter and receiver are on the surface (the ground), then the reflection from it can be neglected, and also to use the formula (1).

Action factors (b) and (c) generally is unknown, but it can be evaluated on the basis of additional information about the terrain.

Factor (d) due to the heterogeneity of the diagrams of the transmitting and receiving antennas. If you can change the orientation of the antenna in space, to eliminate the influence of this factor requires information about their orientation. If such information is not available, you must either request a measurement at a specific antenna orientation (vertical, horizontal, etc.), or to carry out effective filtering incoming data from the beacon. It is desirable that the beacons are fairly evenly distributed over the neighborhood of the locator and the number is sufficiently large.

Action factor (e) manifested usually at sufficient remoteness of the transmitter and receiver from each other (several kilometers or more) and can be accounted for using the weather data.

2.1 Deterministic Models Locations on the Earth's Surface in the Absence of Obstacles

If the beacon is in the line of sight of the receiver, the distance to it is computed directly from the distant characteristic patterns, taking into account:

$$r = F^{-1}(\alpha) = \sqrt{\frac{K_1}{\alpha}} = \sqrt{K_1 \frac{P^T}{P^R}}, \tag{6}$$

$$r = 10^{\frac{K_2 - \beta}{20}}. \tag{7}$$

In this case, the locus is a circle of radius r, the center of which coincides with the beacon. With two beacons locus is a pair of points (the intersection of two circles), while the three — only one point (the intersection of the three circles).

If you know the coordinates $\{(x_k, y_k)\}_{k=1}^{m}$ of the locator beacons are the coordinates (x, y) of the system (the problem is solved multilateration):

$$\begin{cases} (x - x_1)^2 + (y - y_1)^2 = r_1^2 \\ \quad \dots\dots\dots\dots\dots\dots \\ (x - x_m)^2 + (y - y_m)^2 = r_m^2 \end{cases} \tag{8}$$

If the coordinates of the beacons set geographic coordinates (latitude θ and longitude ϕ), it is necessary to consider this curvilinear reference system. However, in a small neighborhood of any point other than the poles, it can be considered a Cartesian (linearized). The distance between the points in this neighborhood is using the metric

$$d\rho = \sqrt{(dx)^2 + (dy)^2} = R\sqrt{(\cos\theta d\phi)^2 + (d\theta)^2},$$

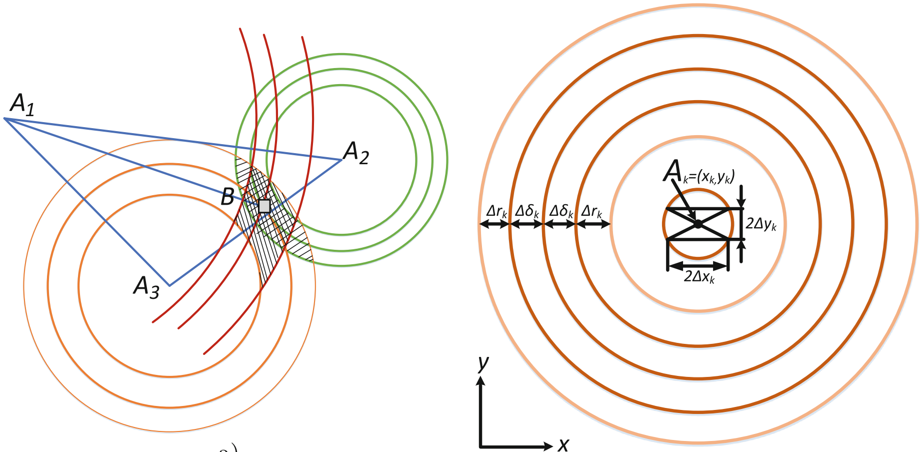
where R — the average radius of the Earth (6367 km).

In view of this problem can be formulated as multilateration

$$\begin{cases} (\phi - \phi_1)^2 \cos^2\theta_1 + (\theta - \theta_1)^2 = (r_1/R)^2 \\ \quad \cdots\cdots\cdots\cdots\cdots\cdots \\ (\phi - \phi_m)^2 \cos^2\theta_m + (\theta - \theta_m)^2 = (r_m/R)^2 \end{cases} \tag{9}$$

2.2 Stochastic Model of Locations on the Earth's Surface in the Absence of Obstacles and Error Estimate

If the power emitted and received signal considered random variables (the process), the distance from the radar to the beacon will also be a random variable (process). At the same loci become "fuzzy" or blurred: the locus of beacons $L = \bigcap_k L_k$ — "fuzzy spot" where L_k — "fuzzy ring" or locus of a single beacon (Fig. 2a).



a)

b)

Fig. 2. The structure of the locus of the three beacons (a) and blur the "ideal" single locus beacon (b)

Calculation of the position locator is based on $RSSI$ values and coordinates of the beacons. Each of these parameters should be considered as a random process. Approximately stochastic component causing blur loci can be considered as additive noise. Options dispersion and determine the amount of noise amplitude blur. From the geometric point of view, blur locus locator for two reasons (Fig. 2b) uncertainty of the center of the circle (the coordinates of the beacon) and its radius (distance from the beacon).

Effective evaluation and analysis of errors output parameters (coordinates locator) can be obtained using total differentials of smooth functions in a deterministic model of the scene.

From (6) we get:

$$dr_k^{(1)} = (F^{-1})'(\alpha_k)d\alpha_k = -\frac{1}{2}\sqrt{\frac{K_1}{\alpha_k^3}}d\alpha_k \tag{10}$$

Since $\alpha_k = 10^{\beta_k/10}$, then $d\alpha_k = \frac{\ln 10}{10}\alpha_k d\beta_k$, then

$$dr_k^{(2)} = -\frac{\ln 10}{20}\sqrt{K_1}10^{-\beta_k/20}d\beta_k, \tag{11}$$

$$d\alpha_k = du(P_k^R, P_k^T) = \frac{1}{P_k^T}dP_k^R - \frac{P_k^R}{(P_k^T)^2}dP_k^T. \tag{12}$$

Here of

$$dr_k^{(3)} = -\frac{\sqrt{K_1}}{2}\left(\frac{P_k^T}{P_k^R}\right)^{3/2}\left(\frac{1}{P_k^T}dP_k^R - \frac{P_k^R}{\left(P_k^T\right)^2}dP_k^T\right), \tag{13}$$

or

$$dr_k^{(3)} = \frac{\sqrt{K_1}}{2}\left(\frac{1}{\sqrt{P_k^R P_k^T}}dP_k^T - \sqrt{\frac{P_k^T}{\left(P_k^R\right)^3}}dP_k^R\right). \tag{14}$$

Let Δr — error (half precision interval estimation) to determine the distance of distant characteristic, ΔP^R, ΔP^T — the power measurement error signal is sent and received, respectively, while

$$\Delta r = dr^{(1)} + o(\Delta\alpha), \tag{15}$$

$$\Delta r = dr^{(2)} + o(\Delta\beta), \tag{16}$$

$$\Delta r = dr^{(3)} + o\left(\sqrt{(\Delta P^R)^2 + (\Delta P^T)^2}\right). \tag{17}$$

Coordinates k-th beacon (x_k, y_k) defined errors Δx_k, Δy_k, respectively (half precision interval estimates), so the error location is the beacon

$$\delta_k = \sqrt{(\Delta x_k)^2 + (\Delta y_k)^2}. \tag{18}$$

The total error in determining the distance to the beacon (half the thickness of conventional “fuzzy ring”) equal to the sum of errors:

$$\Delta d_k = \Delta r_k + \delta_k. \tag{19}$$

A rough estimate of the error location by this method can be obtained by averaging the thickness of “fuzzy rings”:

$$\Delta x := \frac{1}{\sqrt{2}m}\sum_{k=1}^{m}\Delta d_k, \qquad \Delta y := \frac{1}{\sqrt{2}m}\sum_{k=1}^{m}\Delta d_k. \tag{20}$$

Errors in determining the geographical coordinates of the locator on the longitude and latitude are equal

$$\Delta\phi := \frac{\Delta x}{Rcos\theta}, \qquad \Delta\theta := \frac{\Delta y}{R}. \tag{21}$$

2.3 Location on the Plane in the Presence of Obstacles

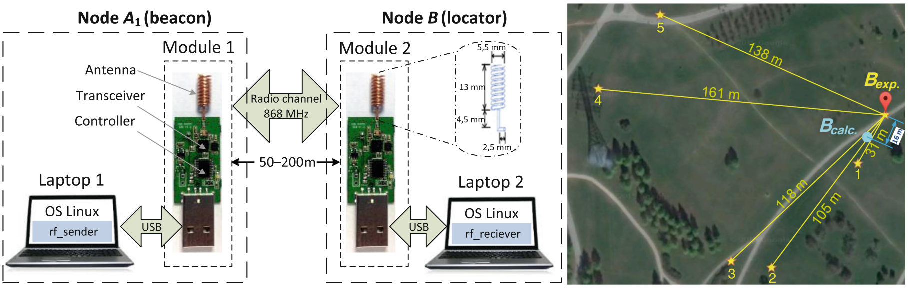
If the beacon is hidden obstacles, the location and the reflection parameters are unknown, the error locations may be prohibitive. To mitigate the impact of obstacles, an effective space-time filtering of data from beacons. Under the temporal filtering is defined here as data processing of each beacon alone received over a certain period of time and under spatial — processing data received from the family of beacons, at the current time.

The essence of the spatial filtering that beacon transmits its position (x_k, y_k) and power P_k^T level, the weight s_k assigned to each beacon. The smaller the distance to the beacon, the effect of interference and noise, the more s_k. Initially, weight unknown, as no known signal conditions (distance, obstacles, interference, noise, etc.). The initial assessment is carried out on the distant weight characteristic, but in the course of the weight is constantly recalculated. The problem multilateration beacon for the whole family and is calculated error in determining the coordinates and the distance to the beacons. Beacons are assigned weights according to the magnitude of the error distance. At the same time it is far from the hidden obstacles or locator beacons, the signal from which the noise is strongly distorted and noise, getting minimum weight. If beacons are in unfavorable conditions for ranging (in buildings, tunnels, forest, etc.), the network must constantly calculate their "internal" weight in relation to other beacons. For example, each beacon can calculate its location to other beacons and to compare the results with satellite navigation. The smaller the difference the higher "internal" weight.

3 Experiment

For the development of the technology has been developed relative navigation layout (Fig. 3) and an experiment on the ground in the field (3b) for the embodiment of a decentralized network in accordance with 1b.

Based layouts are receiving and transmitting device based on TI CC1101 transceiver and microcontroller control ST STM32F0, a set of specially designed programs for reception and transmission of navigation data. In addition, the program shows the level $RSSI$, dBm. The means used are two laptops with the operating system installed GNU/Linux, the two connected wireless transceiver module. The modules, developed by LLC "Open development" [10], are small-sized wireless devices with a USB interface and a spiral antenna [11]. The program runs on a laptop rf_sender beacon and sends the coordinates of the locator, rf_reciever - runs on a laptop locator receives the data shows the level of $RSSI$, calculates its own coordinates.



a) b)

Fig. 3. The circuit layout (a) the location and the result on the ground (b)

Geographical coordinates (θ, ϕ) of the moving area on the beacon A determined through a GPS system and a fixed locator B taken at time points $t_1, \ldots, t_6$ (Fig. 3b). The transmitter power is 16 mW, distance to B the assembly varies in the range of 50–200 m. The conditional boundary between the near and far zones of the helical antenna is located, much less than 1 m. $RSSI$ is averaged over 10 measurements.

Table 1. Experimental data of reference points

Number of beacon, k	Latitude θ_k, degrees	Longitude ϕ_k, degrees	Error δ_k, m	$RSSI$, dBm
1	55.83386801	37.36731450	5	–70,85
2	55.83335085	37.36654756	10	–71,35
3	55.83338211	37.36618881	5	–74,75
4	55.83424147	37.36499766	10	–78,50
5	55.83461404	37.36554843	5	–66,20

The resulting experimental radar coordinates of B for GPS: latitude 55.83410991, 37.36756219, longitude with an error of 5 m.

3.1 Comparing the Experimental Results with the Calculated Values

When calculated in the first approximation consider the directivity pattern uniform, antenna gains believe unit, the accuracy of $RSSI$ believe zero. Below is a sequence of calculation.

(1) Calculate the parameters of the link $K_1 = 7,56 \cdot 10^{-4}$ m, and $K_2 = -31,2$ dBm the formula (4).

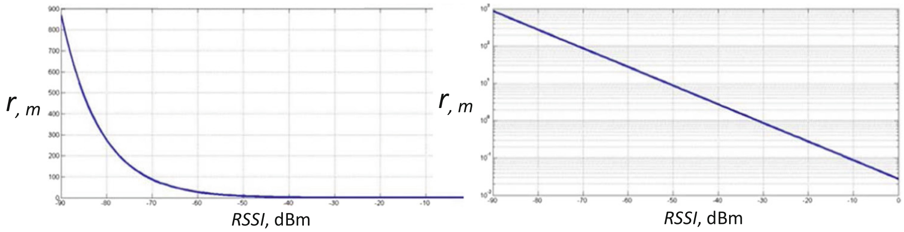


Fig. 4. Distant linear characteristics (a) and logarithmic (b) scale

(2) Find the distance r from the beacon by the formula (7) and distant characteristic (Fig. 4).
(3) Solve the system of equations (6) for the unknowns ϕ and θ to obtain the coordinates of the point estimate locator and obtain $\theta \approx 55.83399999°$, $\phi \approx 37.36739999°$.
(4) To evaluate the error in determining the distance from the formulas (11) and (16), and accept: $\Delta\beta_k = 0$ and, therefore, $\Delta r_k = 0$.
(5) Estimate the total error in determining the distance to the beacon by the formula (19), where the error δ_k of GPS-location beacons given in Table 1.
(6) According to the formula (21) estimate error in determining the coordinates of the locator an average thickness of "fuzzy ring" (interval estimation accuracy coordinate locator) $\Delta x = \Delta d/\sqrt{2} \approx 5\,\text{m}$, $\Delta y = \Delta d/\sqrt{2} \approx 5\,\text{m}$.

The resulting calculated position locator for GPS are as follows: latitude $\theta \approx 55.83399999°$, longitude $\phi \approx 37.36739999°$, with an error of 5 m. The actual discrepancy between calculated and experimental data was 0.0002° (0.72″) in latitude and longitude, which corresponds to 16 m. This discrepancy is due to the chaotic traffic nodes network space and a random arrangement of their antennae, which affects the radiation pattern and $RSSI$.

4 Conclusions

The proposed approach for the relative navigation allows to determine the geographical coordinates of the decentralized network nodes by the method of multilateration and evaluate the error location.

In the case of location on the plane in the presence of obstacles is recommended to use the space-time filtering and temporal filtering eliminates the effect of noise and space, ranging beacons in their accuracy and reliability, eliminates the effect of remoteness and interference caused by the weight of the adaptive system.

An indication of the importance of traffic nodes should be considered as a change of the distance between them at the time of the signal and its processing. This change in distance caused by the movement of nodes to each other and the finite velocity of propagation and signal processing, causing a regular error location. This error can be neutralized by extrapolation of the trajectories of network nodes.

Held in the field experiment on a specially-designed layouts allow to test these theoretical calculations and experimental results are compared with the calculated values confirmed the efficiency of the proposed method relative navigation.

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