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Ambiguity Resolution in ZigBee Phase Shift Measurements Using MAFA Method

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Abstract. This paper presents ZigBee module that is used for ranging in indoor positioning. The system is using the phase shift measurements to determine the distances between user and anchors. The nature of phase shift measurements is causing the results to be in the range of a single wave length. Thus, as in GNSS measurements, appears the problem with ambiguity resolution. In satellite positioning this issue is well described but in range-based ZigBee positioning this problem needs to be solved. The standard procedure to find the correct values of ambiguities is to search for a combination of observation equations with smallest RMS. The authors propose a different solution – the Modified Ambiguity Function Approach (MAFA). It is a method of GNSS carrier phase data processing. In this method, the integer nature of ambiguities is taken into account in the functional model of the adjustment.

Keywords: Indoor positioning, ZigBee, MAFA algorithm, ambiguity.

Conference topic: Technologies of Geodesy and Cadastre.

Introduction

AT86RF233 is a 2.4GHz transceiver (from ATMEL) based on ZigBee protocol. In this device, next to TOF (Disha 2013) module, a phase measurement unit (PMU) is introduced. PMU and TOF modules can be used for a geometry-based positioning or proximity detection. Additionally RSSI can be used for geometry free positioning. Unlike the TOF, where distance is calculated on the basis of the round trip time, in the phase shift method the carrier wave is modulated sinusoidal, and round-trip time is turned into phase shift (Nejad, Olyaee 2006):

$$\Delta\Phi = 2\pi f \frac{2\rho}{c}, \tag{1}$$

where: f – frequency, ρ – geometric distance vector, c – speed of light.

For the purpose of this experiment, to measure the distances, wireless nodes based on the REB233CBB hardware platform with dedicated software (RTB Evaluation Application) were used. Each node consists of REB233SMAD radio extender with AT86RF233 radio transceiver and a PCB with AtxMega256A3 micro-controller. A PC computer is used as a user interface. The communication between PC and REB233CBB is performer using USB. In every single distance measurement two nodes, namely initiator and reflector, are involved. In the ranging initiation phase, which starts with sending a request from initiator, the ranging capabilities are negotiated between initiator and reflector. The request for antenna diversity is included in this stage. After performing subsequent phases, namely timing synchronization and ranging start phase the proper ranging procedure is carried out. This procedure is based on the measurement of a phase shift corresponding to measured distance between nodes (Rapinski 2015; Rapinski, Smieja 2015, Rapinski, Cellmer 2016). It is repeated for a set of frequencies defined during the initiation phase. In the data transfer and distance calculation phases, obtained measurement results are processed according to the Eq. (2) and distances with corresponding DQF values are returned

$$\rho = \frac{c - 1\sum_{N-1} \Delta\Phi n}{4\pi 4\pi \left(N-1\right)\Delta f}, \tag{2}$$

where: N – ambiguity,

Due to the nature of the phase shift measurements, measured distance periodically (after each 75 m) resets to zero. Hence when the device is starting there is a certain ambiguity (N) in the measurement results. The name ambiguity is adapted here from the GNSS phase observations processing. Measured distance can be denoted as:

$$D = \rho + N \times 75.00\left[m\right]. \tag{3}$$

In the Figure 1 it can be observed the behavior of measurement results. The dashed line shows theoretical distance and the solid line shows the measured distance.

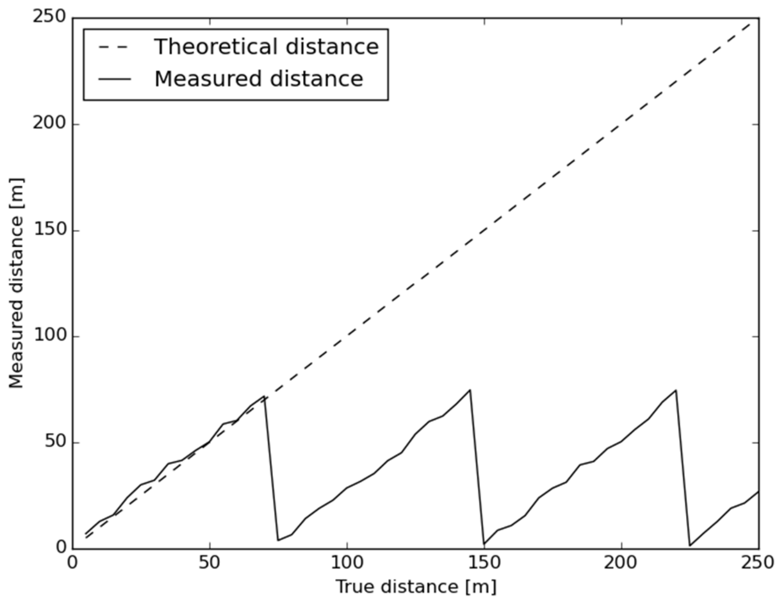

Fig. 1. Measured vs true distance

Ambiguity resolution

The ZigBee phase shift ranging ambiguity and the GNSS phase measurements ambiguity show some similarity. In GNSS positioning the ambiguity problem is widely described (Teunissen, Verhagen 2009). In range-based ZigBee positioning the number of unknown parameter in trilateration with ambiguities is equal to the number of coordinates plus the number of ambiguities (there is one ambiguity for each anchor). In the static GNSS surveys the change in the satellite constellation in two consecutive GNSS epochs provides the supernumerary observables and the change in geometry required for the ambiguity resolution. In the real time GNSS surveys with the on the fly ambiguity resolution, the search procedures are usually used. There are also other, more sophisticated techniques like MAFA method (Cellmer 2011; Cellmer *et al*. 2013). In the indoor navigation the anchors are fixed so there is no change in geometry of the trilateration. If we want to use single epoch, there is more unknowns then observables in the set of equations. This is the reason, why the search procedure must be introduced. The GNSS are using the measurements of a carrier wave phase shift. The carrier frequency for these systems are in the range from 1.164 GHz to 1.610 GHz which corresponds to 0.18–0.25 m wavelength. With this wavelengths the number of candidates for a correct solution can be significant. In case of the ZigBee phase shift ranging, there will be only one or two possible ambiguity values for each anchor. The search procedure presented in this paper assumes the calculation of the solution for all the combinations of ambiguities. Subsequently, the solution is computed for each combination of ambiguities, resulting in the x, y and z coordinates of the user which is the candidate for a correct solution. The number of candidates is equal to the number of all combinations.

One of the procedure to find the correct values of ambiguities is to search for a combination of observation equations with smallest RMS (Janicka, Rapinski 2017) calculated as:

$$RMS = \sqrt{\frac{\sum vv}{n}} \ . \tag{4}$$

The smallest value of RMS is considered as the correct solution. The Figure 2 presents RMS values used for ambiguity resolution.

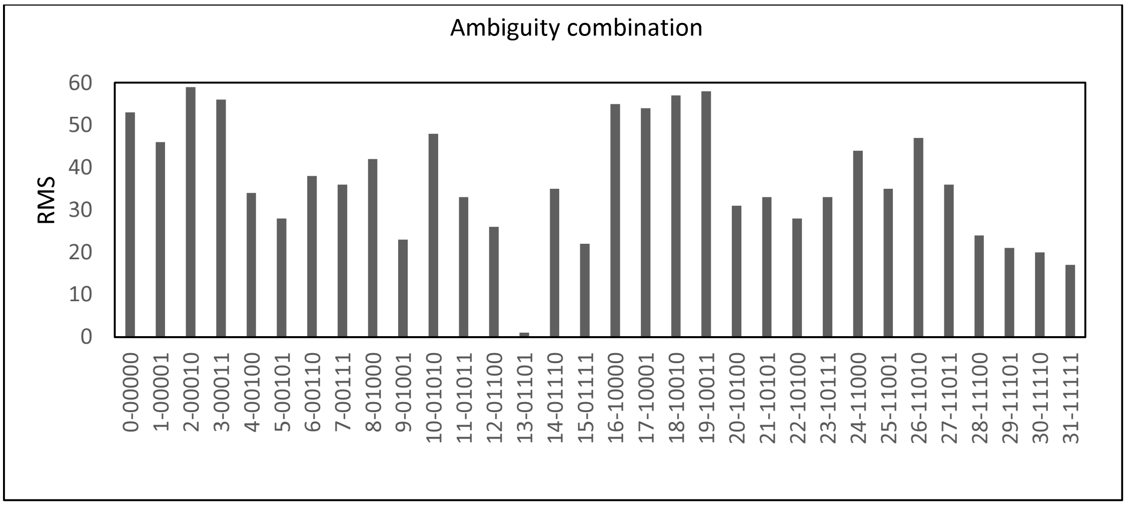

Fig. 2. RMS values used for ambiguity resolution

Modified Ambiguity Function Approach

The Modified Ambiguity Function Approach (MAFA) is a method of GNSS carrier phase data processing. In this method, the integer nature of ambiguities is taken into account in the functional model of the adjustment. The general model of a ZigBee phase shift range measurement can be described as:

$$\Phi + v = \frac{1}{\lambda}\rho(x) + N, \tag{5}$$

where: Φ – vector of phase observations; v – residual vector ($n \times 1$); $\boldsymbol{\lambda}$ – wavelength; x – parameter vector; ρ – geometric distance vector; N – integer ambiguity vector.

Since the residual values is much lower than half a cycle. $v << 0.5$ it can be

$$\Phi + v - \frac{1}{\lambda}\rho(x) = \text{int}\left[\Phi - \frac{1}{\lambda}\rho(x)\right]; \tag{6}$$

$$v = \text{int}\left[\left[\Phi - \frac{1}{\lambda}\rho(x)\right] - \left[\Phi - \frac{1}{\lambda}\rho(x)\right]\right]. \tag{7}$$

The residuals are formed for each of n carrier phase observations. Then the system of these equations is solved with LSA (least square adjustment) method. General formula of the residual equations can be in the following form:

$$v = \frac{1}{\lambda}Ax + \delta, \tag{8}$$

where: $\delta = \text{int}\left(\Phi - \frac{1}{\lambda}\rho^0\right) - \left(\Phi - \frac{1}{\lambda}\rho^0\right)$ – misclosures vector; A – design matrix (n × 3); ρ^0 – geometric distance computed using a priori position.

$$A = \begin{bmatrix} \frac{x - X_1}{\rho_1^0} & \frac{y - Y_1}{\rho_1^0} & \frac{z - Z_1}{\rho_1^0} \\ \frac{x - X_2}{\rho_2^0} & \frac{y - Y_2}{\rho_2^0} & \frac{z - Z_2}{\rho_2^0} \\ & \vdots & \\ \frac{x - X_n}{\rho_n^0} & \frac{y - Y_n}{\rho_n^0} & \frac{z - Z_n}{\rho_n^0} \end{bmatrix}. \tag{9}$$

The least square adjustment problem can be formulated as:

$$v = \frac{1}{\lambda} Ax + \delta; \tag{10}$$

$$v^T Pv = min. \tag{11}$$

The solution of that problem is the following parameter vector:

$$x = -\lambda \left(A^T PA \right)^{-1} A^T P\delta. \tag{12}$$

Measurement results

The proposed method with the smallest RMS value allows to obtain the correct solution. Unfortunately this approach has relatively high numerical cost since the minimization of objective function must be performed many times. In case of relatively small area of the building and small number of anchors it is not a problem. Otherwise it makes more sense to use more efficient solution. To confirm the effectiveness of the proposed method MAFA the calculations were performed. Five anchors and one rover were used. The layout of the experiment is depicted in Figure 3.

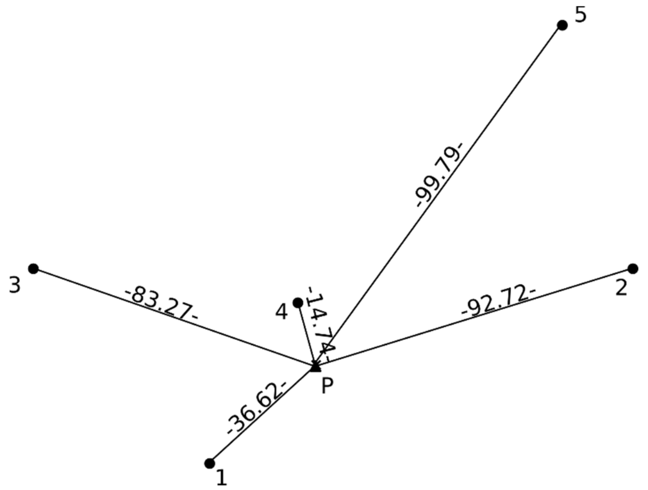

Fig. 3. Geometry of trilataeration

Distances between anchors 1 and 4 were smaller than 75 meters and the rest of distances were greater than 75 m. Thus ambiguities exists for anchors 2, 3 and 5. The maximum value of Ni is assumed to be 1 because the largest measured distance does not exceed 150 m. Figure 4 presents location of five anchors and one stationary rover P.

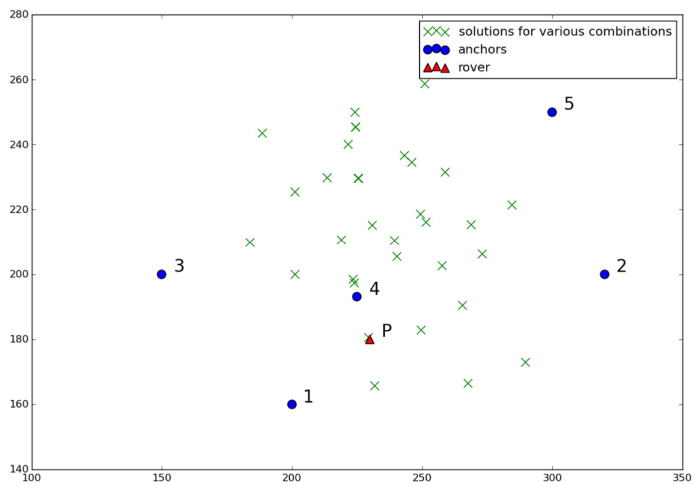

Fig. 4. Positioning results

Figure 4 depicts all of the candidates for the correct solution (marked with crosses). From all candidates only one is close to the true rover position P.

In order to depict the impact of initial coordinates selection on the final result in the MAFA solution the Monte Carlo simulation of 1000 iterations with random initial coordinates was performed. For this simulation the selection of initial each coordinate followed a normal distribution:

x $N(x_{true}; 100)$;
y $N(y_{true}; 100)$;
z $N(z_{true}; 10)$.

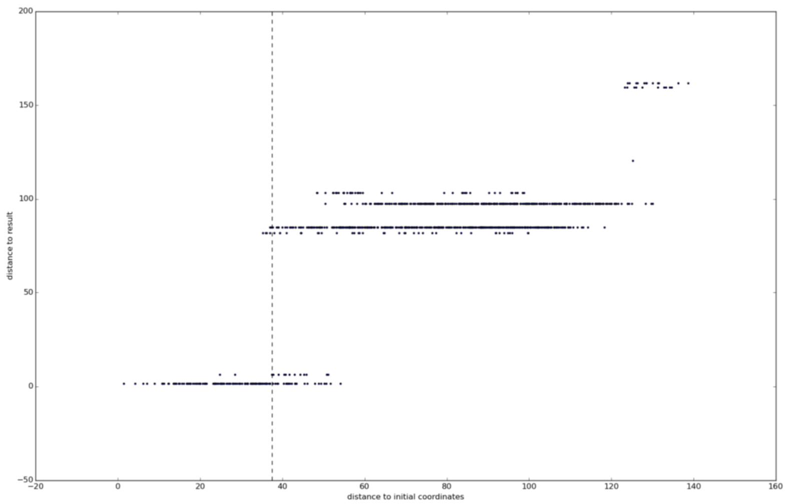

Fig. 5. Monte Carlo simulation

From the last figure it can be noticed that when the v << 0:5 assumption is fulfilled MAFA method is giving correct results (the vertical dashed line is at half wavelength). When the condition is not fulfilled the ambiguity is causing large errors in the solution.

Conclusions

The problem of ambiguity in positioning with ZigBee phase shift measurements and the proposed method of the solution are described in this paper. The similarity to the GNSS phase observation ambiguities is clear however the difference in wavelength makes the ambiguity resolution much easier for the ZigBee system. The application of the search procedure to find a solution with the smallest RMS gives satisfying results. However the computational cost increases when the ambiguities are not known for all of the anchors, there is relatively big number of anchors or the area of the building is relatively large.

In such a case the application of modified ambiguity function approach (MAFA) can be better solution. The application of MAFA method to ZigBee phase shift positioning allows to avoid the ambiguity issue in this kind of measurements. The v << 0:5 condition can be relatively easy assured, because of the long intermediate wavelength used in ZigBee PMU ranging.

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