Real-time Localization for Wireless Sensor Networks with multiple beacon transmissions

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Abstract

This paper proposes and analyses a localization mechanism for Wireless Sensor Networks. The requirement of the proposed mechanism is the use of a fixed small number of beacon transceivers which will be equipped with GPS functionality and able to transmit a gradient of power levels. The several power levels serve to identify the distance by means of power without using the Received Signal Strength Indicator (RSSI). The location estimation is then completed using linear algebra. Due to wide range of applications, the method utilizes Quality of Service (QoS) parameters promising an optimized appliance for each case. This new localization method is fully scalable, power aware and capable to be deployed both in networks with movable or stationary nodes.

Keywords

Localization, Beacon node, Power gradient, Scalability

1. Introduction

The wireless sensor networks are an exciting concept of a wireless network having a wide variety of promising applications in real life. One of the important technical issues that characterize the functionality of this type of networks is the self-localization of nodes. It is often necessary that the data transmitted to the sink of the network are accompanied by the location information. The localization system should be cheap, power-aware and variably accurate depending on the application.

There are several approaches to enable localization functionality for a wireless sensor network; Sivalingham 2004 and Savvides 2001 have provided overviews on this matter. The reference point is either a centroid point, as in (He 2003) and (Bulusu 2000), or more frequently a GPS receiver mounted on a sensor node or used separately. The transceiver that carries the GPS reference position information is called wireless beacon. The beacon broadcasts the reference position information and the random sensor node calculates its position by measuring a metric such as the signal strength (Mondinelli 2004 and McGuire 2003), the time of arrival and direction of arrival (Moses 2002), the time difference of arrival (Rappaport 1996), the angle of arrival (Klukas 1998) or even the antenna directivity (Nasipuri 2002). Moreover, the beacon nodes can be stationary or mobile (Sichitiu 2004), one time used or constantly deployed.

Most of the referenced methods proposed in the literature for localization use the range of communications between the node and the beacon in order to calculate the node position.

These methods are called range-based methods. In general, the range-based methods are highly accurate methods for estimating location. The drawback, however, is mainly the node complexity, the power consumption and the node cost, all of which are very sensitive parameters for the implementation of a sensor node. On the other hand, the range-free solutions offer a low-cost, low-energy approach in estimating locations. He 2003, Bulusu 2000, Lazos 2004 and Ou 2005, all proposed methods where the node localization takes place without the need of specific range estimation equipment. However, accuracy in these methods is typically low and implementation in some application scenarios becomes slow and unrealistic. Energy awareness is studied by Zou 2003 and a general comparison of localization methods is given by Langendoen 2003.

The proposed scheme merges the two above approaches using a variable and small number of GPS beacons and a geometrical method to compute the node position. The localization is based on range estimation, but no range measurements take place in the sensor node. It is organized in a manner of time division transmits and promises very high speed location estimation as opposed to previous methods. This feature is very important in networks where real-time knowledge of mobile node location is needed. Moreover, Ou 2005, explained that high number of beacons increases cost and accuracy as well as restricts scalability. In this paper, the number of beacons is kept low and the accuracy level is used in a QoS tradeoff.

The rest of the paper is organized as such. In section 2, the localization method is described. Accuracy errors, Power consumption and Time response of localization are analyzed in section 3. Finally, in section 4 some application scenarios are presented and the paper is concluded.

2. Description of the localization method

The localization of the sensor nodes is based on the GPS information which is available to the beacon nodes. Instead of RSSI measurements, a different approach is used. Each beacon broadcasts its position *N* times with different power levels. At first, the power levels are low so as not to be detected by the sensor node receiver. Gradually, by increasing the power, and transmitting the information of the step sequence, every receiving node will detect the transmission and save the step information. The procedure is repeated for all beacon nodes in a round robin manner.

In figure 1, an example of the proposed scheme is showcased. The sensor node S1, receives four broadcast packets from B1, B2, B3 and B4, each of which contain the relative beacon GPS coordinates and the step sequence. The level at which this will occur depends on the sensor node receiver threshold which is assumed unknown:

$$P_{N_{thr}} = P_{B_T} \frac{\lambda^2 G_B G_N}{(4\pi)^2 d_i^{\,2}} = P_{B_T} \frac{A}{d_i^{\,2}} \tag{1}$$

Where, P_{Nthr} is the node receiver threshold level, G_b and G_N the gain for the beacon and sensor node antenna respectively, λ the wavelength, P_{BT} the transmit power of the beacon for the i step and d_i the distance between the two transceivers. A is an arbitrary constant.

A calibration is used, in which the power gradient is received by another beacon. In this process, the power gradient is calibrated. Unfortunately, the calibration is valid only for a beacon receiver, which in general is not the same with the sensor node receiver. However, we get:

$$P_{B_{thr}} = P_{B_T} \frac{\lambda^2 G_B G_B}{(4\pi)^2 d_{GPS}{}^2} = P_{B_T} \frac{B}{d_{GPS}{}^2} \tag{2}$$

Where d_{GPS} is the known distance between the two beacons and B is another constant. At this point, the volume of the power step ΔP can be defined so as to have a linear quantization of the space between the transceivers:

$$P_i = \frac{(4\pi)^2 P_{B_{thr}} d_i{}^2}{\lambda^2 G_B G_B} = k_B d_i{}^2 \tag{3}$$

$$\Delta P = P_{i+1} - P_i = k_B (d_{i+1}{}^2 - d_i{}^2) = k_B \Delta d(\Delta d + 2d_i) \tag{4}$$

Where k_B is a constant for the beacon receiver. As a result, the power should be calibrated as shown in figure 2. In the event that P_{Nthr} equals P_{Bthr} and A equals B, the sensor node can calculate its position with no quantization error using only three beacon broadcasts. The calculated d_1, d_2 and d_3 are three circles that pass through the sensor position. The method that estimates the correct position is called trilateration (for information see Navidi 1998). In case the sensor node has a different transceiver from the beacon node, the distances d_1, d_2 and d_3 are found with an analogy:

$$d_1' = kd_1 \qquad d_2' = kd_2 \qquad d_3' = kd_3 \tag{5}$$

Let B1(x_1,y_1), B2(x_2,y_2), B3(x_3,y_3) be the beacon nodes and S(x_0,y_0) the sensor node. The following Cartesian transformation is used:

$$\begin{cases} x_T = \dfrac{(x-x_1)(x_2-x_1)}{d_{12}} - \dfrac{(y-y_1)(y_2-y_1)}{d_{12}} \\ y_T = \dfrac{(x-x_1)(y_2-y_1)}{d_{12}} + \dfrac{(y-y_1)(x_2-x_1)}{d_{12}} \end{cases} \tag{6}$$

$$\text{and, } d_{12} = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2} \tag{7}$$

And the new coordinates will be B1(*0*,*0*), B2(d_{AB},*0*), B3(x_3',y_3') and S1(x,y); x, y and k can be calculated by the system of equations:

$$\begin{cases} x^2 + y^2 = k^2 d_1{}^2 \\ (x-d_{12})^2 + y^2 = k^2 d_2{}^2 \\ (x-x_3')^2 + (y-y_3')^2 = k^2 d_3{}^2 \end{cases} \Rightarrow \begin{cases} y^2 = k^2 d_1{}^2 - x^2 \\ x = \dfrac{d_{12}{}^2 - k^2(d_2{}^2 - d_1{}^2)}{d_{12}} \\ ak^4 + bk^2 + c = 0 \end{cases} \tag{8}$$

where:

$$\begin{aligned} a &= h_2{}^2 + 4y_3' h_1{}^2 \\ b &= 2h_2 h_3 + 4y_3'(d_{12}h_1 - d_1{}^2) \\ c &= h_3{}^2 + y_3' d_{12}{}^2 \end{aligned} \quad \text{and} \quad \begin{aligned} h_1 &= \frac{d_1{}^2 - d_2{}^2}{2d_{12}} \\ h_2 &= (d_3{}^2 - d_1{}^2) + \frac{x_3'(d_1{}^2 - d_2{}^2)}{d_{12}} \\ h_3 &= x_3' d_{12} - x_3'^2 - y_3'^2 \end{aligned} \tag{9}$$

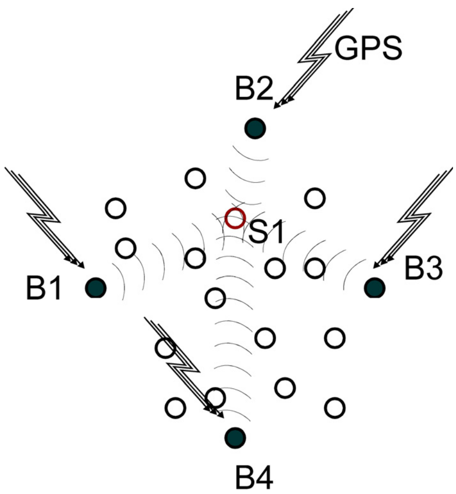

Figure 1 – Topology of the sensor network. B1, B2, B3 and B4 are beacon nodes equipped with GPS receiver.

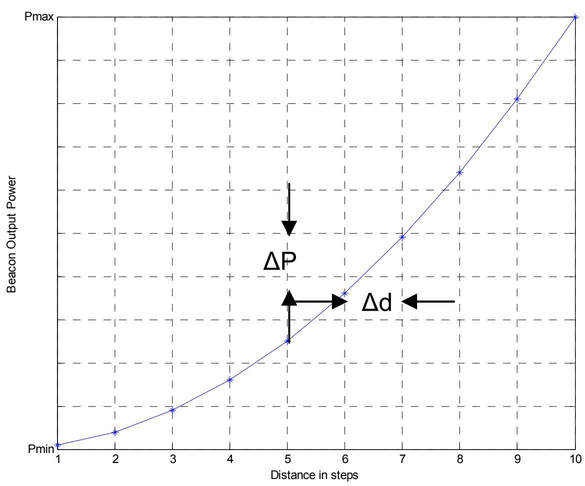

Figure 2 – Beacon Output Power gradient for *N*=10 steps. The power increment should be of the power of 2 for the space to be linear.

The solution is two cases of k. As k increases, the common solutions of circle d_1 and d_2 are running towards opposite directions. The upper point (s1) becomes the first common solution with circle d_3. The second case is subject to the velocity of the second point (s2) and the point c2 on the d_3 circle, which for a proper large k will be identical with s2. Since both points are running towards the same direction, the velocity of c2 should be greater than that of s2.

In order to decide upon the correct solution (between the two), topology information is required. This can be obtained either by pre defining the three beacons position and proper software, or by using a fourth beacon. If the cost of a beacon node is an issue, then the software solution should be chosen. If the randomness during installation process is more important, then the fourth beacon should be included in the scheme. In figure 4, the area in bold defines the boundary between the two cases. When, the node position is inside the area, the smaller root of the two should be chosen. When the node position is outside the area, the greater solution will be the correct one. The curve between the two areas is an ellipse and it is given by equation 10.

$$y = \frac{\left(x_3'^2 + y_3'^2 - x_3' d_{AB}\right) \pm \sqrt{4 y_3'^2 \left(x d_{AB} - x^2\right) + \left(x_3'^2 + y_3'^2 - x_3' d_{AB}\right)^2}}{2 y_3'} \quad (10)$$

2.1 Equipment Requirements

From the above it follows that the proposed scheme requires four functional beacon nodes each of which should have a GPS receiver, a location estimator and the ability to transmit a gradient of power levels (figure 1). The sensor nodes should only be equipped with the ability to make some simple calculations in order to estimate their position by means of trilateration.

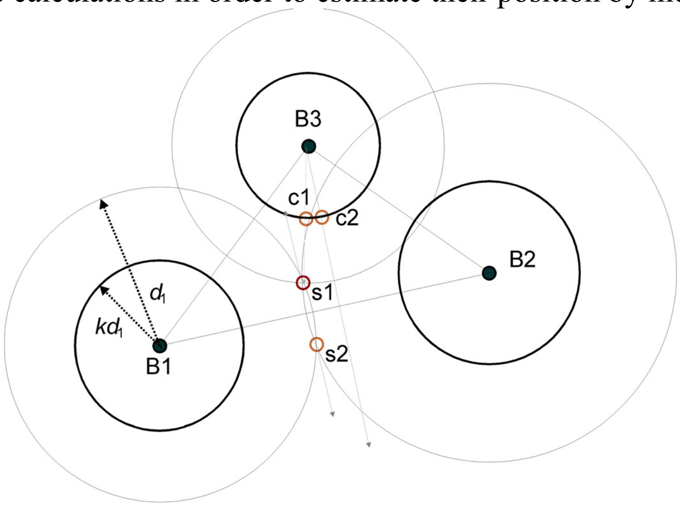

Figure 3 – Restoring position information at the sensor node (s1). The three bold circles are scaled in order to find two possible solutions.

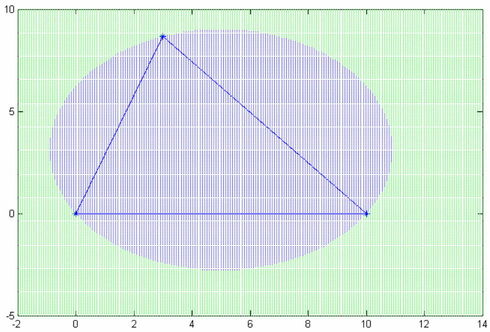

Figure 4 – When the node is known to reside inside the dark area the smaller solution of the two is correct, otherwise the greater should be chosen.

2.2 MAC modifications

Two new sink commands should be introduced for the proposed scheme to be functional, the calibration command and the measurement command. After a calibration command, the beacon nodes calibrate their transceivers and configure their dynamic range. The sensor nodes remain with their transceivers powered off. After a measurement command, the beacon nodes broadcast the calibrated power gradient in a round robin sequence. In the same time, the sensor nodes turn their receivers on until the first power level reaches them. Then, they shut the receiver down and schedule a restart for the next beacon broadcast. The calibration command takes place before a measurement command and only on the occasion that calibration information does not exist or it is considered unreliable. The measurement command is used whenever the location information needs to be updated.

3. Performance evaluation

According to the scheme, the node receives three GPS coordinates and some relative distances from these points. The following steps are necessary for node position estimation.
1. The three coordinates are transformed using 6.
2. The ratio k is estimated using one of the ways mentioned above and tested against some stored values.
3. With backward substitution the position coordinates are obtained.
4. The coordinates are retransformed using the inverse transformation of 6.

In this procedure, errors may arise in several measurements. GPS measurements are subject to GPS errors. The method itself, introduces a quantization error which is relative to d_{max}/N. Finally, one of the transmissions can be hindered by an electromagnetic obstacle. It is obvious that the error performance of this model can be improved by means of elaborate algorithms. In this paper, the error estimation will be limited to quantization error. The performance over several values of N will be tested in terms of accuracy, power consumption and measurement loading and delay giving a tradeoff between those design parameters.

3.1 Error Estimation

The quantization error will be a uniform random variable with values $[0,\Delta d]$. This error affects all three R_1, R_2 and R_3 estimations, resulting in a new estimation of k and respectively new x and y values. We define the error proportions:

$$\frac{|\tilde{x}-x|}{d_{\max}}, \frac{|\tilde{y}-y|}{d_{\max}} \text{ and}$$

$$\frac{|\tilde{r}-r|}{d_{\max}} = \frac{\left|\sqrt{\tilde{x}^2+\tilde{y}^2}-\sqrt{x^2+y^2}\right|}{d_{\max}} \tag{11}$$

Where $\tilde{x}$, $\tilde{y}$ and $\tilde{r}$ are the estimated values, x, y ,r are the real values and d_{max} is the maximum distance used in the calibration which represents the volume of the area in use.

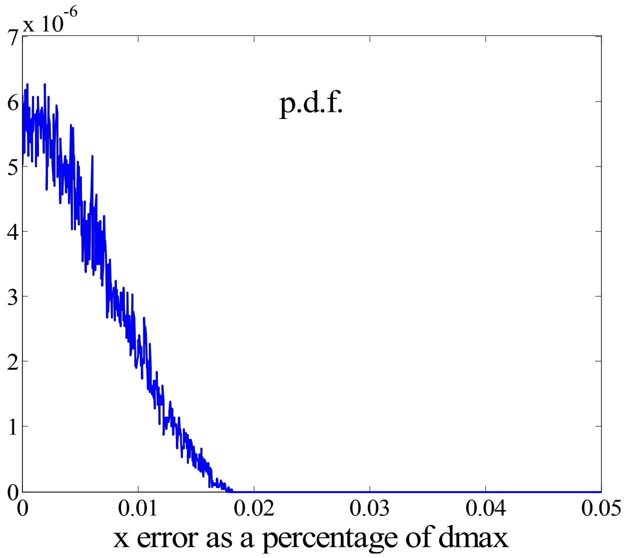

Figure 5 – Probability Density Function for *x* coordinates error as a percentage of d_{max}.(*N=30*)

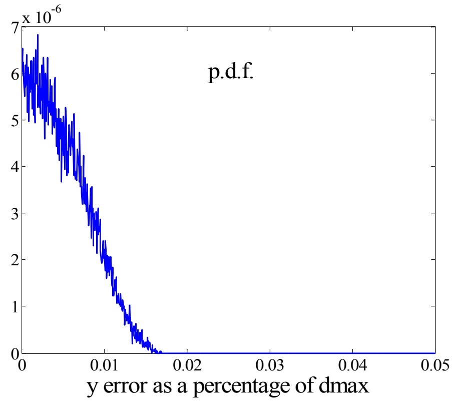

Figure 6 – Probability Density Function for *y* coordinates error as a percentage of d_{max}.(*N=30*)

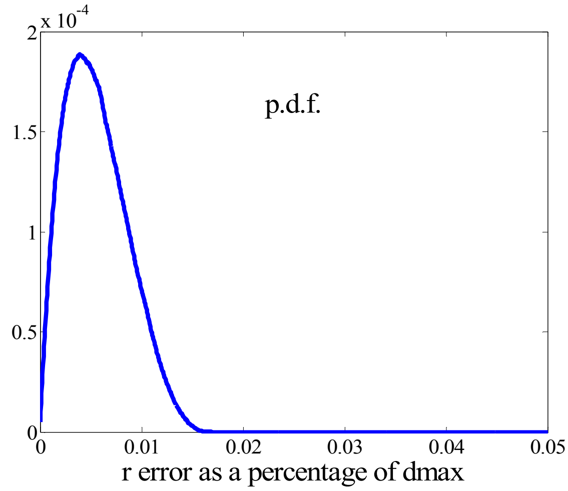

Figure 7 – Probability Density Function for radial error as a percentage of d_{max}.(*N=30*)

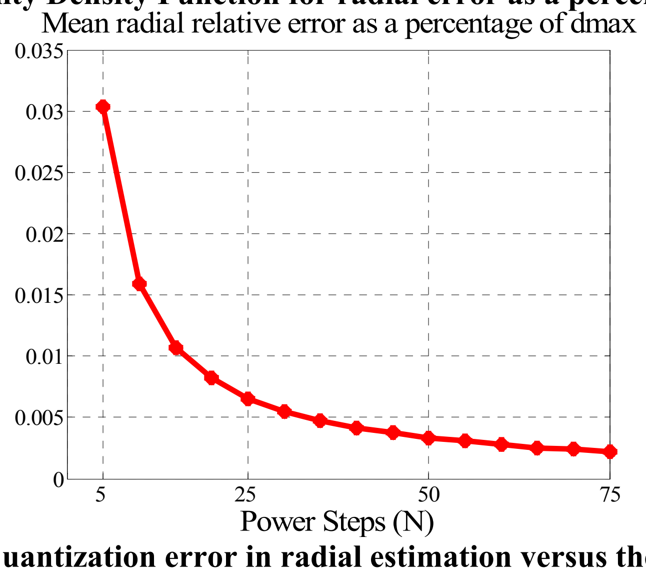

Figure 8 – Mean quantization error in radial estimation versus the number of power steps.

In figure 8, the mean radial error is presented versus the number of steps in the power incrementing. As *N* gets greater, the quantization gets smaller and the mean error decreases. For an case study where the nodes are scattered in a area *100m x 100m*, from figure 8 we get that for accuracy *1m*, *N* is required to be set to 20.

3.2 Power Estimation

As mentioned above, the receiver of each node is turned on as long as the node is waiting for the beacon broadcast. This time span varies according to the position of the node relative to the positions of the beacons and the value of N. As regards the topology, the best performance is obtained when the node is positioned on the gravity centre of the triangle B1B2B3. When the node is close to one of the vertices the increase in power consumption is unimportant. The increase becomes important when the node receiver is situated outside the triangle area. In figure 9, the power performance is estimated as a function of N and E_R, where E_R is the energy that the receiver consumes when idle for one packet duration. The results are also dependent on the ratio k which is assumed having a typical value of 0.8 (this assumes that the beacon receiver is 25% better than a simple node receiver). It should be noted, that for scenarios with random positioning of beacons and/or larger number of beacons, the power consumption increases.

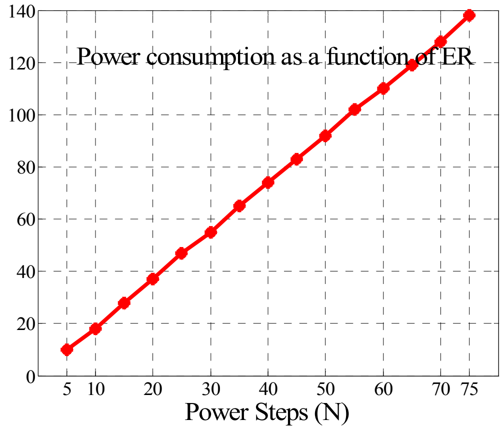

Figure 9 – One measurement power consumption versus power steps for the worst case scenario. The node is near the edges of the triangle B1B2B3.

3.3 Network Loading and Delay

Assuming a packet duration of t_p, the measurement time t_M can be found:

$$t_M = 3(N+1)t_p \tag{12}$$

One packet duration is used at the end of a beacon transmission as a separation period between the three transmission rounds.

Regarding the network loading, it is obvious that no communications can take place during a measurement or calibration command. As such, the network loading depends on the position updates. If a position update is required every t_u, then the network loading is $200\frac{t_M}{t_u}\%$, for a network with beacon mobility and $100\frac{t_M}{t_u}\%$ for stationary beacons. This happens because in the second case, no recalibration is required.

4. Conclusion

The advantages of the proposed scheme are that it uses a small number of beacons, it has fast measurement time and small loading of the network and it does not require RSSI measurements or any complex equipment. The disadvantage is that the accuracy is limited by uneven terrain and obstacles. As a conclusion, the proposed scheme is attractive in a great number of scenarios. It provides easy position estimation when real time position is needed with a small number of beacons. Moreover, it can be used in one time measurements with removal of beacon nodes.

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