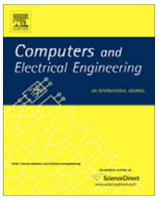
ARTICLE IN PRESS

Computers and Electrical Engineering xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng



Technical Communication

Angle-of-arrival localization based on antenna arrays for wireless sensor networks ☆

Paweł Kułakowski [a,*], Javier Vales-Alonso [b], Esteban Egea-López [b], Wiesław Ludwin [a], Joan García-Haro [b]

[a] Department of Telecommunications, AGH University of Science and Technology, Poland
[b] Department of Information Technologies and Communications, Polytechnic University of Cartagena, Spain

ARTICLE INFO

Article history:
Received 28 July 2009
Accepted 29 March 2010
Available online xxxx

Keywords:
Wireless sensor networks
Localization techniques
Angle-of-arrival
Smart antennas
Outdoor environments

ABSTRACT

Among the large number of contributions concerning the localization techniques for wireless sensor networks (WSNs), there is still no simple, energy and cost efficient solution suitable in outdoor scenarios. In this paper, a technique based on antenna arrays and angle-of-arrival (AoA) measurements is carefully discussed. While the AoA algorithms are rarely considered for WSNs due to the large dimensions of directional antennas, some system configurations are investigated that can be easily incorporated in pocket-size wireless devices.

A heuristic weighting function that enables decreasing the location errors is introduced. Also, the detailed performance analysis of the presented system is provided. The localization accuracy is validated through realistic Monte-Carlo simulations that take into account the specificity of propagation conditions in WSNs as well as the radio noise effects. Finally, trade-offs between the accuracy, localization time and the number of anchors in a network are addressed.

1. Introduction

Wireless sensor networks (WSNs) attract the attention of telecommunication world incessantly from at least 10 years. They promise multiple possible applications, e.g. monitoring an environment in dangerous regions, controlling traffic in streets, controlling an inventory in storehouses, tracking patients in hospitals or monitoring enemy forces in a battlefield. In most of these applications, data gathered by sensors should be associated with sensor positions and it is worthless without information about the place of its origin. Thus, it is crucial that sensors know their positions with the aid of a localization algorithm.

Despite the huge research effort, there is still no well-accepted approach on how to solve the localization issue, especially for outdoor sensor networks. Because of large number of sensor nodes and their desirable low cost, it is not feasible to mount a GPS receiver at each node. There have been a large number of localization techniques proposed so far [1–4], but there is no consensus on the existence of a simple, accurate, decentralized and energy efficient solution suitable for WSNs. The expensive ultra-wideband (UWB) techniques [5] give a very decent localization accuracy, but only in indoor environments, where the distances between the sensors are very limited. The similar weakness concerns the systems based on the transmission of acoustic waves [6,7]. Moreover, the acoustic transmission requires an additional hardware that increases the system cost. A

☆ Reviews processed and proposed for publication to the Editor-in-Chief by Associate Editor Dr. Sahin.

* Corresponding author. Tel.: +48 12 617 3937.
E-mail address: kulakowski@kt.agh.edu.pl (P. Kułakowski).

0045-7906/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compeleceng.2010.03.007

Please cite this article in press as: Kułakowski P et al. Angle-of-arrival localization based on antenna arrays for wireless sensor networks. Comput Electr Eng (2010), doi:10.1016/j.compeleceng.2010.03.007

good accuracy could be obtained with the algorithms based on the time-of-arrival calculations, but the simple sensor transceivers are not able to perform such exact measurements. Finally, there is a group of thoroughly investigated and promising techniques based on the received signal strength (RSS) levels. However, it was shown that they cannot guarantee the appropriate precision [8,9], also because of the difficulties with matching the channel model parameters with the real propagation conditions [10].

Also, the real WSN deployments, test-beds and measurements confirm the doubts concerning the localization techniques. Good results are reported for the indoor networks [7,11], especially when the sensors are deployed in a single room, however with the aid of additional UWB or acoustic hardware. For the outdoor scenarios, the measurements are either very limited [12], the accuracy is not satisfactory [10] or the localization issue is neglected and left unsolved [13,14]. Clearly, the problem lacks a proper solution.

Localization in WSNs can be also performed using angle-of-arrival (AoA) measurements. In this work, the idea of the AoA localization system where some sensor nodes are equipped with directional antennas is developed and carefully analyzed. Having in mind the requirements and objectives of outdoor WSNs, the focus is on a simple solution that could be incorporated into small wireless sensors, while still being accurate enough for WSN applications.

The contribution of the paper is as follows. First, an AoA localization system concept suitable for small-size sensor nodes is described. Then, the detailed performance analysis is presented showing that the system is very promising even in adverse propagation conditions. Also, to refine a well-known least-squares algorithm, a new heuristic weighting function is proposed. It enables combining the information from all the anchors more effectively and reducing the location errors. The algorithm is validated by Monte-Carlo simulations using sensor parameters typical for MICAz motes [15] and a realistic propagation model [16,17]. To the best of authors knowledge, it is the first paper where the influence of Signal-to-Noise Ratio on the AoA localization accuracy is taken into account in the simulations. Finally, the trade-offs between the accuracy, localization time and number of anchors are exemplified, analyzed and discussed.

The rest of the paper is organized as follows. In Section 2, we address the related work in the area of AoA localization schemes. The specific technique analyzed in this paper is described in Section 3 and then, its accuracy is validated in Section 4. In Section 5 the AoA technique is compared to other proposals and finally, in Section 6, some conclusions are given and scope of future research is outlined.

2. Related work

While the angle-of-arrival localization is a well-known technique and thoroughly described in the open literature, there are not many papers dealing with AoA schemes appropriate for wireless sensor networks and their specific objectives, requirements and applications.

In Refs. [18,19], AoA schemes are described where sensor nodes are forwarding their bearings with respect to anchors, i.e. nodes which are assumed to know their own coordinates and orientations. Unfortunately, these methods require a strong cooperation between neighbor nodes, and they are prone to error accumulations. In Ref. [20], anchor nodes with adaptive antennas are used to communicate with sensors located in different parts of a network. A similar concept in Ref. [21] assumes a single anchor in the center of a network sending an angle bearing. The other nodes calculate their coordinates with the aid of the bearing and some extra information from their neighbors. However, both these solutions also need some RSS data. The idea of anchor nodes with sector antennas was also presented in Ref. [22]. There, the position of a sensor node is determined as an intersection of antenna sectors of different anchor nodes. More precise algorithms assume that sensors can receive exact AoA information from anchors [23,24]. This can be accomplished if the anchors have directional antennas rotating with a constant angular speed. The sensors can estimate the AoA of the signal registering the time when the rotating beacon has the strongest power. However, in Ref. [23], the anchors with unrealistic radiation patterns are analyzed, the radio noise is not taken into consideration and the calculations are possible only for three anchors. In Ref. [24], the rotating antennas are too large for tiny anchor nodes. Finally, a common idea of a lighthouse was adapted to wireless sensor localization in Ref. [25], but it suffers the same frailty of unfeasibility and additionally requires the optical communication between the anchor and the sensors. Generally, the main challenge of the AoA localization schemes for WSNs is the difficulty in achieving good accuracy while keeping the system simple and feasible to implement in pocket-size devices.

3. Algorithm details

Taking into account the difficulties mentioned above, a solution is sought that could combine the simplicity and localization accuracy suitable for the applications of outdoor WSNs. It is proposed that each anchor in the considered network be equipped with an array of four antennas ($\lambda/2$ dipoles) arranged in a square with a diagonal equal to $\lambda/2$ (6.25 cm for the 2.4 GHz band). By changing the direction of maximum radiation of the antenna array, a rotating beacon is created. In order to do that, the phases of the signals at all four antennas are adjusted to have four radio waves interfering constructively at a specific direction, according to the well-known scanning phased array (beamforming) technique [26]. The obtained radiation pattern has a maximum directivity between 6.8 dBi and 8.1 dBi (depending on the required azimuth of the beacon) and the half-power beamwidth between 63° and 75°. Despite such a large beamwidth, the localization errors of the algorithm, pre-

Please cite this article in press as: Kułakowski P et al. Angle-of-arrival localization based on antenna arrays for wireless sensor networks. Comput Electr Eng (2010), doi:10.1016/j.compeleceng.2010.03.007

sented in Section 4, are rather small. At the same time, the chosen antenna parameters guarantee the whole antenna array would be very small and appropriate for tiny devices.

The issues of medium access control (MAC) protocols are beyond the scope of this paper. Thus it is assumed that the anchors are able to transmit their beacons in turn, one after another, or a specific MAC protocol exists that organizes the anchor transmissions. The presented localization scheme does not require perfect synchronization between anchors, but their transmissions should be separated. Each anchor starts by sending its own position and a short omni-directional pulse. Then, it emits a beacon with a rotating radiation pattern. The main direction of the beacon is changed every T seconds by a constant angular step $\Delta\alpha$. A sensor registers the time when the beacon power is the strongest. A difference in time between reception of the initial pulse and the maximum of the beacon power (Δt) allows calculating the angle-of-arrival of the signal:

$$\alpha = \Delta\alpha \cdot \Delta t / T \tag{1}$$

The angle α_i (from the i-th anchor) can be used in an equation binding the coordinates of the anchor and the sensor:

$$X - x_i = (Y - y_i) \cdot \tan\alpha_i \tag{2}$$

where $[X \quad Y]$ and $[x_i \quad y_i]$ are the coordinates of the sensor and the i-th anchor, respectively. If the angles of arrival from two or more anchors are known, the sensor can estimate its position using a standard least-squares approach [27]. The appropriate system of equations can be written as:

$$A \cdot c^T = b \tag{3}$$

where

$$A = \begin{bmatrix} 1 & -\tan\alpha_1 \\ 1 & -\tan\alpha_2 \\ \vdots & \vdots \\ 1 & -\tan\alpha_n \end{bmatrix}, \quad c = [X \quad Y] \quad \text{and } b = \begin{bmatrix} x_1 - y_1\tan\alpha_1 \\ x_2 - y_2\tan\alpha_2 \\ \vdots \\ x_n - y_n\tan\alpha_n \end{bmatrix}$$

The estimated coordinates of the sensor can be calculated as:

$$\hat{c} = \left((A^T A)^{-1} A^T b\right)^T. \tag{4}$$

Assuming the radio noise is additive and Gaussian, it significantly disrupts determining the time when a beacon has the largest power, especially if the average signal-to-noise ratio (*SNR*) at the sensor antenna is low. Additional refinements can be performed in order to make the algorithm less vulnerable to the radio noise and adverse anchor positions (as *SNR* depends on the distance between the anchor and the sensor). First, sensors can sample the beacons multiple times per each beacon azimuth to take average values and filter out the noise. This obvious solution helps to reduce the noise level, but it also extends the time of the whole localization procedure and, in consequence, increases the energy consumed by sensors for listening. This trade-off is shown more clearly in Section 4. In the simulations presented, the beacons are sampled 10 times, unless otherwise stated.

Also, each sensor can define a weighting coefficient for every beacon to fulfill the two following goals. On the one hand, the importance of an anchor should be proportional to the received power, because large received power results in a large probability of a correct AoA detection. On the other hand, the standard least-squares approach is biased, as the anchors with AoA close to 90° or 270° have a stronger influence (because of tangent function) on the calculation of sensor positions than the others. This should be corrected by the appropriate normalization factor. Thus, for the i-th anchor, the following coefficient is proposed:

$$m_i = P_i / (1 + |\tan\alpha_i|) \tag{5}$$

where P_i is the maximum power of the signal received from the i-th anchor. The weighting coefficients can be taken into account in the least-squares approach:

$$\tilde{A} \cdot c^T = \tilde{b}, \tag{6}$$

where

$$\tilde{A} = \begin{bmatrix} m_1 & -m_1\tan\alpha_1 \\ m_2 & -m_2\tan\alpha_2 \\ \vdots & \vdots \\ m_n & -m_n\tan\alpha_n \end{bmatrix} \quad \text{and} \quad \tilde{b} = \begin{bmatrix} m_1x_1 - m_1y_1\tan\alpha_1 \\ m_2x_2 - m_2y_2\tan\alpha_2 \\ \vdots \\ m_nx_n - m_ny_n\tan\alpha_n \end{bmatrix}$$

The simulation results reveal that the multiple sampling and the weighting coefficients are crucial for the accuracy of the AoA localization. Without the refinements, the location errors of the presented algorithm are 60–70 % (only 1 sample) or 40–220 % (without the coefficients) larger. The authors tried a broad spectrum of weighting coefficients, but the ones proposed by (5) gave the best performance.

Please cite this article in press as: Kułakowski P et al. Angle-of-arrival localization based on antenna arrays for wireless sensor networks. Comput Electr Eng (2010), doi:10.1016/j.compeleceng.2010.03.007

It should also be mentioned that the AoA localization is very robust to any kind of large-scale fading, e.g. shadowing. To calculate an AoA, a sensor compares the power levels of the signals received from a single anchor. If a large-scale fading occurs, it affects all these signals equally, thus the final AoA measurement is not distorted.

4. Accuracy validation

The accuracy of a single AoA measurement can be assessed analytically using the Cramer-Rao lower bound [28]. However, the localization accuracy of the whole system is a consequence not only of the AoA measurements, but the relative positions of the anchors and the parameters of the localization algorithm. Thus, Monte-Carlo simulations were conducted than took into account the random positions of nodes and anchors, the radio propagation channel model specific for outdoor WSNs, the radio noise and the transceiver parameters of real sensor motes.

The WSN simulation scenario consisted of 100 sensors and a variable number of anchors. All the sensors and anchors were located randomly, with a uniform distribution, in an area of 50 m × 50 m, and remained static during the network operation. Each anchor had an array of four antennas and it emitted a rotating beacon. The parameters of wireless nodes were based on MICAz motes operating in the 2.4 GHz band [15]. The transmission power of anchors was equal to 0 dBm and the radio noise power at the receivers was 100 dBm (the noise factor was 11 dB and the frequency bandwidth was 2 MHz). The path loss was calculated according to a propagation model specific to WSNs working in a rural environment at 2.4 GHz [16,17]:

$$\text{Path Loss [dB]} = 40 + 29.9\log_{10}d + s, \tag{7}$$

where d is the distance in meters between a transmitter and a receiver, and s is a log-normal random variable representing shadow fadings with a standard deviation of 3.5 dB.

The obtained results are presented using *RMSE*: an average root mean square error of the sensor positions. In some cases, there was a small percentage of nodes that could not be localized, i.e. *RMSE* was very large due to their very adverse position related to anchors positions. Though, their number was always less than 0.02% of the total number of sensors. All the simulations were repeated at least 5000 times and all the 95% confidence intervals of *RMSE* were smaller than 2% of the measured values.

In Figs. 1 and 2, the overall performance of the localization algorithm is shown. In Fig. 1, *RMSE* is given as a function of the angular step of the beacon rotation for different numbers of anchors in the network. There is an obvious trade-off between the rotation step, number of anchors and the localization accuracy, though decreasing the step below 1° is rather not worthwhile, as a smaller step results in a longer time of the localization procedure and larger energy expenditure regarding the transmission and reception. With six anchors in the network, the localization accuracy is about 2 m. With 10 anchors, *RMSE* can be decreased to 1.2 m. Excellent accuracy can be obtained for 20 anchors, but such a large number is evidently impractical. The anchors were located randomly in the considered area. A planned deployment of anchors could increase the localization accuracy; however it is not possible in all WSN applications.

AoA localization accuracy could be additionally improved if *SNR* at sensor antennas was increased. In many WSN applications, large transmission power is not desirable, however, *SNR* can be also increased by decreasing the noise power. This fact can be exploited when the sensors are working in a narrowband system. If there is no interference from other wireless

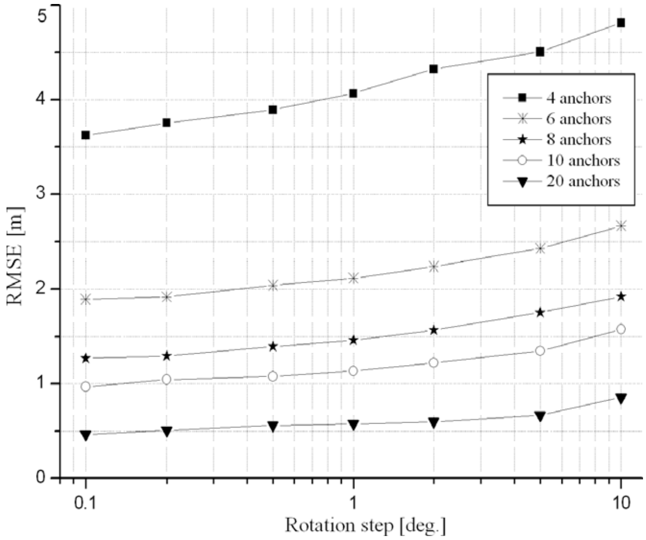


Fig. 1. Localization accuracy as a function of a step of the rotating beacons in a network of 100 sensors and variable number of anchors.

Please cite this article in press as: Kułakowski P et al. Angle-of-arrival localization based on antenna arrays for wireless sensor networks. Comput Electr Eng (2010), doi:10.1016/j.compeleceng.2010.03.007

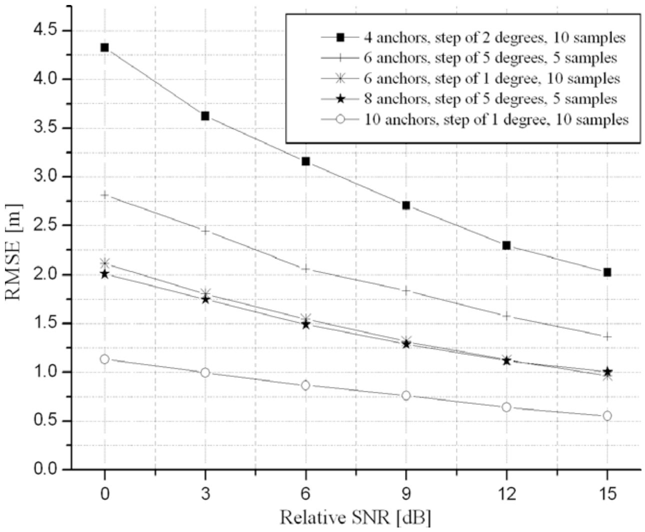


Fig. 2. The influence of average *SNR* at sensor receive antennas on localization accuracy.

systems, the noise power is proportional to the occupied bandwidth. Thus, the localization accuracy can be enhanced if the frequency bandwidth is limited. It should be also noted that such accuracy enhancement would not be feasible in RSS based localization techniques because of the destructive influence of wireless channel fadings.

Some interesting cases with increased *SNR* are depicted in Fig. 2. The reference level $SNR = 0$ dB corresponds to the simulation results presented in Fig. 1. For average *SNR* 15 dB higher, the rotation step of 2° and only four anchors, the location error of 2 m can be achieved. On the other hand, very low *RMSE* (about 0.5 m) is feasible with 10 anchors. A trade-off between the number of anchors and the localization time is also shown: the accuracy of 1 m is possible for six anchors and the rotation step of 1°, as well as for eight anchors, the rotation step of 5° and only five samples per each beacon azimuth. A lower number of samples or larger rotation step obviously results in decreasing the accuracy. On the other hand, then, the entire localization process is completed faster, so sensors save some energy that would be otherwise expended for receiving longer beacons.

5. Accuracy discussion

In the considered network, due to its density, there was approximately one sensor per a square of 5 m × 5 m. Six anchors were sufficient for each of 100 nodes to be localized with the average error of 2–2.5 m. Hence, in such a scenario the sensors are able to correctly match the gathered data with the respective area.

To give a better understanding of the obtained results, some experiments from the open literature are quoted below. Nonetheless, it is not straightforward how to compare the obtained accuracy results with other related research, as there are no reference scenarios suitable for WSN localization algorithms. The reported investigations are performed with different set-up conditions. Consequently, this should be taken into account when making any comparisons.

In Ref. [24], the experimental indoor AoA localization data can be found, showing the average errors of 2.5–4 m for the network with 4–7 anchors located in the area of 20 m × 60 m. The results probably would be better in an outdoor environment, as the non-line-of-sight conditions (typical for indoor scenarios) and multipath radio propagation deteriorate the accuracy of AoA or RSS techniques. On the other hand, the theoretical works on AoA schemes [23] report a very good localization precision of approximately 0.5 m with only three anchors in 75 × 75 m field, but in idealized conditions (no radio noise, very small half-power beamwidth of beacons, anchors placed in the corners of the field).

Comparing with other localization schemes, AoA techniques seem to be very well suited for outdoor WSNs. Some recent RSS measurements [10] show the accuracy of approximately 10 m in the network with eight anchors distributed in 35 × 35 m field. Another lately proposed RSS technique DV-Loc [29], which is an enhancement of the well-known APS system [30], achieves only 5–10 m localization precision for the network with 32 anchors in the 92 m × 92 m area. Very good accuracies of 10–15 cm are reported for UWB systems [11], but the distances from sensors to anchors should be about 5–10 m, what make these systems appropriate rather for indoor applications.

6. Conclusions and future work

Considering the localization dilemma for in-expensive WSNs, the angle-of-arrival techniques fit very well to the requirements of outdoor networks. AoA schemes, particularly the concept described in this paper, do not require any sophisticated

Please cite this article in press as: Kułakowski P et al. Angle-of-arrival localization based on antenna arrays for wireless sensor networks. Comput Electr Eng (2010), doi:10.1016/j.compeleceng.2010.03.007

hardware for sensors, as the system complexity is moved to anchors, which are only a small percentage of the entire network. At the same time, because of the possible trade-offs between the accuracy, localization time and the number of anchors, the demonstrated scheme is very flexible and can be easily adapted to a specific WSN application. The whole algorithm is working in a decentralized manner and no signals need to be transmitted from the sensors to the anchors. It is especially advantageous in large-scale WSNs where the scalability of the applied solutions is crucial for the proper system performance.

The AoA technique discussed in this paper was carefully analyzed, taking into account the appropriate propagation model and the noise effects. The obtained results encourage to continue the investigations. As a future work, two directions of the studies will be conducted. First, it is planned to prepare the physical implementation of the described localization scheme. Commercially available digital phase shifters will be used that could adjust the phases of the signals at all the four antennas in each anchor node. Also, the MICAz motes will be reprogrammed to calculate their positions with AoA measurements. Within the network consisting of anchor prototypes and MICAz motes, not only real measurements of the localization accuracy would be possible, but also the actual assessment of the energy depletion in the anchors and sensors. The second line of the research will concern the integration of the localization schemes with other protocols for WSNs. This will include performance studies of the geographic routing assuming the localization errors specific for the AoA technique. Also, the role of anchors in WSNs could be broadened or redefined to exploit their potential for other functionalities, e.g. in network clustering or data gathering and compressing.

Acknowledgements

This work was supported by Polish project grants 179/N-COST/2008/0 and DWM/MOB17/II/2008. It was also supported by Spanish grant TEC2007-67966-01/TCM (CON-PARTE-1) and developed in the framework of “Programa de Ayudas a Grupos de Exelencia de la Region de Murcia, Fundacion Seneca”.

References

[1] Karl H, Willing A. Protocols and architectures for wireless sensor networks. John Wiley and Sons; 2005.
[2] Stojmenovic I, editor. Handbook of sensor networks algorithms and architectures. John Wiley and Sons; 2005.
[3] Patwari N, Ash JN, Kyperountas S, Hero III AO, Moses RL, Correal NS. Locating the nodes: cooperative localization in wireless sensor networks. IEEE Signal Process Mag 2005;22:54–69.
[4] Wang C, Xiao L. Sensor localization under limited measurement capabilities. IEEE Network 2007;21:16–23.
[5] Gezici S, Tian Z, Giannakis GB, Kobayashi H, Molisch AF, Poor HV, et al. Localization via ultra-wideband radios. IEEE Signal Process Mag 2005;22:70–84.
[6] Frampton KD. Acoustic self-localization in a distributed sensor network. IEEE Sensors J 2006;6:166–72.
[7] Mangas E, Bilas E. FLASH: fine-grained localization in wireless sensor networks using acoustic sound transmissions and high precision clock synchronization. In: Proceedings of 29th IEEE international conference on distributed computing systems, Montreal; 2009. p. 289–98.
[8] Hightower J, Borriello G. Location systems for ubiquitous computing. IEEE Comput 2001;34:57–66.
[9] Awad A, Frunzke T, Dressler, F. Adaptive distance estimation and localization in WSN using RSSI measures. In: Proceedings of 10th Euromicro conference on digital system design architectures, methods and tools, Lubeck; 2007.
[10] Rahman MZ, Kleeman L. Paired measurement localization: a robust approach for wireless localization. IEEE Trans Mobile Comput 2009;8:1087–102.
[11] Ubisense company website. http://www.ubisense.net.
[12] Zein-Sabatto S, Elangovan V, Cheu W, Mgaya R. Localization strategies for large-scale airborne deployed sensor networks. In: IEEE symposium on computational intelligence in multicriteria decision-making, Nashville; 2009.
[13] Mainwaring A, Polastre J, Szewczyk R, Culler D, Anderson J. Wireless sensor networks for habitat monitoring. In: Proceedings of first ACM international workshop on wireless sensor networks and applications, Atlanta; 2002. p. 88–97.
[14] Hartung C, Han R, Seielstad C, Holbrook S. FireWxNet: a multi-tiered portable wireless system for monitoring weather conditions in wildland fire environments. In: Fourth international conference on mobile systems applications and services, Uppsala; 2006. p. 28–41.
[15] MICAz CC2420 2.4 GHz IEEE 802.15.4/ZigBee-ready RF transceiver specification. http://focus.ti.com/lit/ds/symlink/cc2420.pdf.
[16] E-MORANS scenarios (from IST-NEWCOM project) – sensor networks scenario. http://grow.lx.it.pt/web/cost2100/contributions.html.
[17] Verdone R, Dardari D, Mazzini G, Conti A. Wireless sensor and actuator networks – technologies, analysis and design. Academic Press; 2008.
[18] Niculescu D, Nath B. Ad hoc positioning system (APS) using AOA. In: Proceedings of 29th IEEE conference on computer communications (Infocom), San Francisco; 2003. p. 1734–43.
[19] Peng R, Sichitiu ML. Angle of arrival localization for wireless sensor networks. In: Proceedings of third IEEE conference on sensor and ad hoc communications and networks, Reston; 2006. p. 374–82.
[20] Kucuk K, Kavak A, Yigit H, Ozdemir C. A novel localization technique for wireless sensor networks using adaptive antenna arrays. In: Proceedings of IEEE radio and wireless symposium, Orlando; 2008, p. 483–6.
[21] Qu H, Wicker SB. Anchor-free localization in rapidly-deployed wireless sensor networks. In: Proceedings of IEEE conference on mobile adhoc and sensor systems, Vancouver; 2006. p. 627–32.
[22] Lazos L, Poovendran R. SeRLoc: robust localization for wireless sensor networks. ACM Trans Sensor Networks 2005;1:73–100.
[23] Nasipuri A, Li K. A directionality based location discovery scheme for wireless sensor networks. In: Proceedings of first ACM international workshop on wireless sensor networks and applications, Atlanta; 2002. p. 105–11.
[24] Elnahrawy E, Austen-Francisco J, Martin RP. Adding angle of arrival modality to basic rss location management techniques. In: Proceedings of second international symposium on wireless pervasive computing, San Juan; 2007. p. 464–9.
[25] Romer K. The lighthouse location system for smart dust. In: First international conference on mobile systems applications and services, San Francisco; 2003. p. 15–30.
[26] Balanis CA. Antenna theory: analysis and design. John Wiley and Sons; 1997.
[27] Langendoen K, Reijers N. Distributed localization in wireless sensor networks: a quantitative comparison. Comput Networks 2003;4:499–518.
[28] Gezici S, Survey A. A survey on wireless position estimation. Wireless Pers Commun 2008;44:263–82.
[29] Boukerche A, Oliveira HABF, Nakamura EF, Loureiro AAF. DV-Loc: a scalable localization protocol using Voronoi diagrams for wireless sensor networks. IEEE Wireless Commun 2009;16:50–5.
[30] Niculescu D, Nath B. Ad hoc positioning system (APS). In: Proceedings of IEEE global telecommunications conference (Globecom), San Antonio; 2001. p. 2926–31.

Please cite this article in press as: Kułakowski P et al. Angle-of-arrival localization based on antenna arrays for wireless sensor networks. Comput Electr Eng (2010), doi:10.1016/j.compeleceng.2010.03.007