Wireless Sensor Networks and Beyond: A Case Study on Transport and Logistics

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***Abstract*—Wireless Sensor Networks provide opportunities even outside their usual application domain of environmental monitoring. In this paper we present a case study on the use of Wireless Sensor Networks for the control and management of transport and logistics processes. In this study nodes will track all activities, and check for errors that might occur in the process of handling and distributing goods. The nodes will be programmed to warn when errors occur, and keep an activity record of the entire process. An overview of the current situation, and the errors that occur therein, is given. A system architecture is described that can solve or reduce the current problems by incorporating a Wireless Sensor Network in the process.**

***Index Terms*—Context awareness, High-level languages, Localization, Wireless Networks, Intelligent sensors**

I. INTRODUCTION

THE increasing interest in the field of Wireless Sensor Networks (WSNs) has already led to extensive studies concerning the new challenges that researchers and programmers have to overcome: energy efficiency, scarce computing and storage resources, unreliable communication, harsh environments, etc. Therefore, most of the initiatives have focused on tackling these difficulties rather than providing rich functionality within complex world scenarios. Consequently, usual applications utilize sensor nodes for monitoring or tracking purposes within a rather static pattern: collect data, perform some in-network processing (optional) and forward results to a central system.

Recent initiatives try to enhance this vision by transferring additional intelligence and responsibility to sensor nodes, as they are proximate to the point of action. Based on these considerations, we have started to investigate the ways in which they become beneficial and usable in complex real-world applications.

The contribution of this paper is to extend the range of functionality of WSNs beyond what centralised, monitoring-purposes schemes can provide. It does so by describing a case study of the use of WSNs in a transport and logistics process.

The paper is organized as follows: First, an outline of the current situation is given, and a disposition of the problems that occur as a result of the limitations of the current way of operating. Following, a description is provided of how these problems might be overcome if WSNs are used. Furthermore, our proposed solution is addressed.

II. A CASE STUDY: TRANSPORT AND LOGISTICS PROCESSES

A. *Process outline*

This section gives a general overview of a transport and logistics process. Obviously, these processes differ dependent on the type of product, its physical shape, climate requirements, etc. But basically it involves the transportation of goods from a factory or supplier to the end customer.

In many cases, the actual products are placed on or inside Returnable Transport Items (RTIs), such as pallets, carts, containers, or trailers. After delivery of the products, the RTIs will be returned to the supplier and reused in a future delivery.

In our case study, the RTIs in question are rolling containers. These rolling containers are mostly used in retail distribution and have the characteristic that they can be dismantled when they are not transporting goods and in that way take up less space. The rolling containers are a valuable asset. Keeping track of where they are and that – in the end – they are returned to the distribution center is an important issue.

Currently, the distribution process of our case study is partly automated by an Optical Barcode System (OBS). Tracking is achieved by attaching order-associated barcodes to RTIs, but position and state of an RTI is only monitored when an employee actually scans the code and submits it to the system; a time-consuming and error-prone activity that only allows for discrete-time tracking. Years of deployment have proven the value of the OBS, but the yield in functionality has reached its maximum.

The distribution process of our case study starts at a warehouse where an order picker will get an order list, construct an RTI, pick the requested products from the warehouse shelves, and put them in the RTI. Once the RTI is full or the order is complete, the order picker will put a sticker with a barcode on the RTI, which henceforth uniquely identifies that particular RTI. Then, the RTI is moved to the expedition floor. A large grid is painted on the expedition floor and each cell of the grid is associated with a certain distribution route. The RTIs belonging to a single order and/or

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certain distribution route are grouped together. Once a trailer arrives, the RTIs are moved into the trailer according to a loading list that guarantees optimal unloading at the retail stores. A truck will then pull the trailer and deliver the goods to one or more retail stores. Upon arrival at a retail store some or all the RTIs are unloaded from the trailer. If available, previously delivered dismantled RTIs are loaded into the trailer, to be returned to the distribution center.

B. *Major sources of errors*

Due to the fact that the entire process relies on a number of activities performed by employees, it is common for faults to occur. The barcode, for example, needs to be scanned at several stages: after assembling an RTI to be associated with an order, scanning and verifying completeness and the loading sequence of an order, etc. Keeping track of the status of a certain order is carried out by means of the scanning activities, and is vulnerable to faults. And because RTIs are placed in cells with only the employee, order pick list and barcode for verification, misplacement of RTIs is a reoccurring source of errors.

Improving the actual system requires a thorough analysis of the problems that presently occur. The most frequent errors are caused by the following:

- an RTI is filled with wrong goods
- environmental conditions are not the proper ones for the products
- RTIs are placed in a wrong cell on the expedition floor
- RTIs are lost somewhere on the expedition floor
- the expedition floor lacks space for static allocation of cells, resulting in ad-hoc, error-prone solutions
- delays are encountered when gathering the RTIs on the expedition floor
- RTIs are placed in the trailer in an inefficient manner
- RTIs are placed in the wrong trailer
- RTIs are not returned from retail stores

III. REQUIREMENTS

As the above list shows, many of the current problems occur as a result of incorrect handling of the RTIs at various stages of the distribution process. We aim at improving the process efficiency by attaching WSN nodes to RTIs, and consequently make the RTIs an active component.

This section describes the requirements of the improved distribution process, which will ensure the reduction or removal of the most common causes of errors currently experienced. The use of a WSN also opens up opportunities for other improvements to the process, based on the environmental monitoring capabilities of WSNs.

A. *Functional requirements*

- RTI-order association can be automated. The scanning activity is removed from the process thus reducing the employee's workload, and position and state of RTIs can be maintained near real-time.
- Placement of RTIs within cells of the expedition floor can be monitored and guided by the system, and immediate action can be taken if an RTI is positioned in a wrong cell.
- The system can be used to dynamically allocate RTIs to the grid. As a result, allocated space for the expedition floor can be reduced and usage of cells increased.
- Correct trailer loading can be verified to make sure that all and only the correct carts are loaded, and positioning within trailer is correct according to the sequence in which RTIs will be unloaded at the retail stores.
- The environmental monitoring capabilities of WSN nodes can be used to boost quality of the distribution process. WSN nodes have the capabilities to continuously monitor environmental values within an area of importance, close to the actual products. Especially when it involves delicate and perishable goods (such as flowers) this functionality is of high value.
- A complete registration can be made: Which RTI was delivered to which customer, and which RTIs were returned.
- Complete monitoring of the entire distribution process also creates the possibility to record and log all activity of relevance in conjunction with environmental data. When products are delivered in a damaged condition, the cause and responsible party can be identified by merely backtracking logged data.

IV. FUNCTIONAL COMPONENTS AND SOLUTION OUTLINE

The rich set of application requirements and the global complexity of the process results in numerous functional demands that the sensor nodes have to accomplish. This section presents the decomposition into functional components, as well as the specific problems and the techniques we are using to overcome them.

A. *Networking*

The following details allow a quick view on the quantitative aspects of the application: each trailer can be loaded with up to 60 RTIs and on each RTI there are approximately 5 sensors. If we take into account that the expedition floor can hold up to 10,000 RTIs, then we end up with a maximum of 50,000 sensor nodes that have to collaborate in order to achieve the goals stated in the functional requirements. Moreover, this happens within a relatively small geographic area, therefore the huge density of sensors represents a unique challenge.

Due to this high density of nodes, connectivity, node heterogeneity, network dynamics, collisions, and the transmission medium – to mention a few – deserve consideration. Connectivity is directly related to the coverage of a single node, and therefore transmission range needs to be suited to fit the average node density. As it is likely for RTIs to be fitted with different kinds of nodes combined with an environment filled with beacons, gateways, and specific nodes for employees, such a heterogeneous surrounding introduces both possibilities and limitations to the networking protocols. Frequent states of high mobility of RTIs impose additional constraints.

But above all, a major factor inherent to WSNs is energy efficiency which means that the network needs to make optimal use of its resources to ensure a long lifespan, preferably similar to that of RTIs. The necessity for a frugal MAC protocol that minimizes collisions and is able to effectively deal with mobility and errors, is obvious. Especially focusing on energy competence, EMACs [1] and SMAC [2] come to mind, but recently LMAC [3], a TDMA-based protocol, showed to increase network lifetime by a factor 3 compared to the aforementioned. Routing protocols for WSNs are a much researched topic. A detailed survey is given by Al-Karaki et al. [4] and the challenge is to find a suitable algorithm, or adjust or combine existing ones to cope with the ultra-high node density.

B. *Rules*

The WSN nodes will be outfitted with knowledge about the tasks and the rules that need to be enforced, as well as relevant data, such as the role of the particular node in the whole process. Additionally, nodes will obtain information about the process at hand through the use of their sensors, and by communication with other nodes.

Nodes are employed with a set of rules. These rules describe the conditions that the nodes need to guard. For example, while on the expedition floor, each node will continuously verify whether it is located in the designated cell. These rules will be stated as machine-understandable statements of allowable states or situations, and the alerts that must be given when otherwise. For certain nodes, the process they need to monitor consists of several states. RTIs will be either on the expedition floor, inside a trailer, or delivered to a customer. The rules must specify how a node can decide upon the current state, either by directly observing it through its sensors or communication with other nodes, or by detecting events that trigger a change of state.

Different nodes will have different tasks, and as a result, need to have different rules. Besides, from time to time, the rules for each node may change, because of changes in the business processes, or as a result of bug-fixes. It will therefore be crucial that the rules embedded in the nodes can easily be reprogrammed on the fly.

C. *Data model*

The Wireless Sensor Network that will bring about the described scenario needs to deal with more complicated data than just sensor readings. Nodes will need to keep information about where they believe they are, on the expedition floor or inside a certain trailer, properties associated with their location, like the destination of the trailer, and various kinds of other, local and dynamic information, like the destinations of other RTIs in the same trailer.

Furthermore, in cooperation, the nodes will have to retrieve the necessary information from different sources. Destinations of trailers and pallets might be stored in a central database; the order-RTI association is provided by the order picker. The data that a node needs to have, and requests from other nodes, depends on the rules that need to be verified.

D. *Context awareness*

Above all, wireless sensor networks derive their merit from their ability to observe the real world. Nodes can share the sensed data by communication with other nodes, and in this way build an extended set of knowledge about the current situation of their environment. Interpretation of such sensor data is usually referred to as context awareness.

The rules that a node carries can also describe how sensor data should be interpreted. This allows the nodes to keep track of the process it needs to monitor.

Certain kinds of context information can be derived directly from other nodes. All the nodes are equipped with data describing their role in the business process, like the kind of equipment they are attached to, or the location of this equipment.

E. *Localization*

As in many other WSN applications, sensor readings and other context information only have true value when they can be associated with a certain time and location, a statement that holds true for this case as well. Therefore a reliable localization scheme is needed that has adaptive traits, as the functional demands of such a scheme differ with respect to the environment of the RTI and the varying number of resources the environments provide. RTIs come in many different shapes and sizes, and position accuracy is related to the RTIs dimensions. For an RTI of e.g. 1x1 m to not be placed in a wrong cell, position errors should preferably be < 1 m. This results in the need for a fairly fine-grained, highly accurate localization scheme as RTIs need to be associated with a certain cell of the grid. Furthermore, RTIs that are near the expedition floor should not be seen as being positioned on the grid.

Within a trailer, however, it is the sequence of RTIs that is of importance. Basically this constraint reduces the need for an absolute positioning mechanism and, thus, a local or relative mechanism suffices. Nevertheless, the localization issue within a trailer – or any other transport vessel (e.g. train wagon) – is more complex than inside the distribution center. This is due to the fact that some transportation vessels might or might not provide resources to the RTIs' nodes. Trailers owned by the company are likely to have a gateway with a GPS link to the central system possibly in combination with several beacons, but trailers of third party transport companies are not as likely to have a similar infrastructure.

V. PROPOSED SOLUTION

Based on the requirements listed in section III, we have devised a design that will enable the required functionality. All RTIs used in the distribution process will be equipped with one or several WSN nodes. The nodes on the RTIs will communicate with each other wirelessly, creating an ad-hoc network.

A fixed infrastructure of special-purpose sensor nodes is placed regularly in a grid above the expedition floor. These nodes are referred to as beacons and will enable the localization process. They will also act as communication gateways between the RTI nodes and a central coordinator; a computer system in charge of coordinating all actions within the system.

The coordinator will store all data relevant to the global system's functionality. It will make available all the data that RTI nodes need for proper operation, like the trailer that will transport them and their designated cell on the expedition floor. All mobile nodes will also report their activity to the coordinator where it will be recorded in activity logs. The coordinator also takes care of allocating the expedition floor to the RTIs.

Figure 1 shows the process diagram. Three major components can be identified. On the left the order picking process is shown, which is considered to be a pipeline of RTIs. Following, the filled RTIs are relocated via the point of transfer on the expedition floor, in the middle of the diagram. It shows the grid cells, surrounded by beacon nodes, and groups of RTIs placed within the cells, which will be transported together in the same trailer. The right part shows a loaded trailer, containing RTIs for different retail stores. Network connections between beacons in the expedition floor and on the trailer are indicated with dashed lines.

A. *Rule engine*

We will make use of a special purpose task description language. This language is used to describe the rules, and sufficiently provides features to deal with the different kinds of data, and their relationships. This task description language will make use of and will be supported by a communications abstraction framework that hides the details of communication among nodes and sharing information. It will also be used to query a node's sensors, and access other low-level functionality, like timing and synchronization, localization, and network status.

From the requirements stated in section III some properties of the task description language and communications framework can be derived:

- The language should be focused towards specifying a rule that can then be verified by the runtime system. These rules should be dynamic, i.e. will not be hard-coded into the control software running on the nodes.
- The nodes deal with various kinds of data, and from different sources. Sensor data that is generated locally and other data communicated over the wireless links. The task description language rules should be able to operate on both of these, in order to interpret their meaning.
- Data and relationships should easily be captured and shared among all participating nodes in the network. These will be stored in a shared database that can be accessed, as well as altered by all of the participating nodes. This database can be used as an efficient way of sharing knowledge between nodes.
- Nodes may often need to directly exchange data. The abstraction framework should provide the appropriate communication abstractions to efficiently take care of this.
- Whenever necessary, rules carried by the nodes can be changed or updated. Transfer of rules to the nodes must be possible after the network is in operation, and should be done in an efficient way. A compact and flexible representation of the rules will therefore be required.

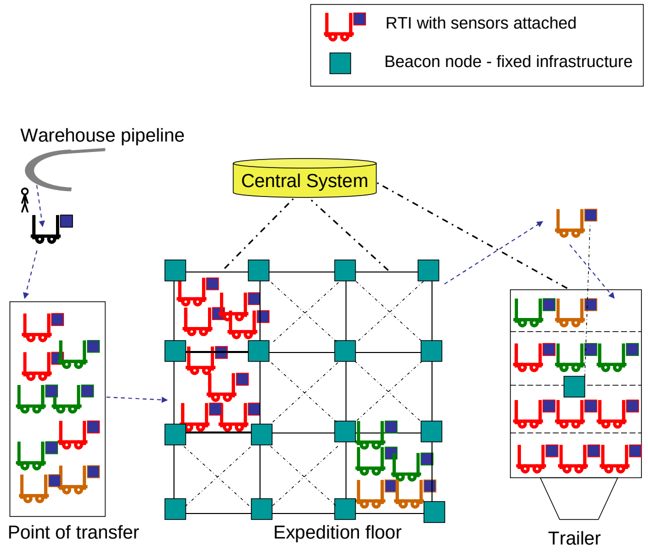

Fig. 1. Process diagram. RTIs gather on allocated grid rectangles within the expedition floor, and they get loaded into a trailer according to a precise loading list.

B. *Localization*

In the previous section we have outlined the need for localization support. This is a topic that has received much attention, and a wide variety of solutions have already been developed. Section VI elaborates more extensively on existing localization systems.

Although addition of specialized hardware on the nodes – which is needed for e.g. ultrasound localization – allows for additional information about placement and distance of other nodes or beacons and thus has the potential to increase localization accuracy, it dramatically increases costs. Furthermore, some specialized hardware is quite vulnerable to shocks or rough handling or not usable at all since it requires line-of-sight.

A measurement that (often) does not require specialized hardware is Received Signal Strength Indication (RSSI), but usability is still a point of discussion and dependent on the environment of deployment and quality of the transceiver [5][6]. The high density of nodes, the fact that RTIs are made of metal and the absence of reliable experimental RSSI data for our scenario, led to the decision to initially make use of connectivity information only. We intend to look for ways in which the – for WSNs – unusual high density of nodes in combination with a fairly resource-rich, static environment offer a new angle to overcome the localization dilemma.

A centralized localization system is considered to not be useful as it involves thousands of nodes interacting with the central system; it puts a huge demand on the gateways, and also creates an impractical network load. One-hop localization schemes (e.g. GPS) have the characteristic that nodes can directly contact beacons and thus – in contrast with multi-hop variants – offer a way to reduce network load and demand less resources. Unfortunately, most one-hop positioning systems have the drawback that they rely on line-of-sight (e.g. the Lighthouse Location System [7]) Furthermore, a coarse-grained localization scheme is needed in other areas of the distribution center and complete beacon coverage is not guaranteed. Also, trailers might have no beacons and rely on the nodes only to retrieve relative position information, thus expressing the need for a multi-hop scheme. Nevertheless, a dynamic approach to the localization problem is imaginable, dependent on the environment and the amount of available resources.

VI. RELATED WORK

Many of the aspects involved in our work have been studied within the area of WSNs. However, an all encompassing system solution that provides the functionality our case study needs has not yet been developed. This section gives a brief overview of previous research related to the different aspects of our system.

Communication protocols that support the ad-hoc and energy efficient nature of WSNs have undergone much study already. Higher level programmability has gained interest in recent years as well. TinyDB [8] is one such example, which uses a high level language to specify the networks task, interpreted locally on the nodes. The Maté [9] virtual machine takes this idea a step further, and allows a wider range of functionality to be programmed. Both systems are specifically built for data gathering WSNs.

Other projects have aimed at integrating low-cost intelligent sensors into everyday objects, like the MediaCups [10] by Beigl *et al.* and the Smart-Its Friends [11] by Holmquist *et al.* But rather than using the objects as independent acting entities, these projects aimed at detecting and supporting the user's activities.

Siegemund designed a special purpose language, SICL [12], translatable to object code, also incorporating context-awareness and data-sharing mechanisms. This is a system developed primarily for context-based user interaction, however.

Probably the closest match to our goals is the work by Strobach *et al.* on Cooperative Artefacts [13]. In this work embedded sensing devices collaborate to achieve a common task, based on description in a prolog-like language. Both domain knowledge and sensor observations are used for this purpose. However, many of the crucial requirements, like localization and centralized data storage are not available.

Research to high level programming support in the form of communications abstraction has produces some results already as well. Hood [14] and Abstract Regions [15] are two such systems. Both systems supply a set of functions to easily create shared variables that are accessible by a predefined group of nodes. However, since both are developed for the TinyOS architecture they are not usable in our work.

Localization has been a prime topic in WSN research. Numerous prototypes have been developed that make use of range measuring hardware based on infrared (e.g. Active Badge [16]), ultrasound (e.g. Active Bat [17], Cricket [18]) and RSSI (e.g. RADAR [19]). Although this list seems impressive, they do not build on WSNs in particular, and the number of large, actual deployments of WSNs capable of performing localization is small.

We are primarily interested in distributed, range-free algorithms that provide either absolute or relative coordinate systems. Among the most popular are DVHop [20] and MDS-MAP [21]. DVHop is actually one of a group of algorithms that combine two major ideas: distance vector routing and GPS. MDS-MAP is a positioning technique leading to results superior to most of all the other existing alternatives. Several versions of the algorithm have been developed: both range free and range based, centralized and localized. They can produce both relative and global coordinates. Far more algorithms with varying performance exist: a detailed overview on positioning is given by Niculescu [22], whereas Langendoen et al. [23] give a detailed comparison of distributed localization algorithms.

An interesting new approach is Sequential Monte Carlo [24]. It is an adaptation of the Monte Carlo positioning technique used in robotics. Although we are primarily focusing on static scenarios, RTIs can be highly mobile and this scheme targets such a scenario. The results are completely counter-intuitive: they show that mobility improves localization results at a reduced communication and computation cost. More amazing, the original scheme is range-free and the initial work shows results comparable to the distributed localization schemes for static scenarios. These characteristics make it an interesting option for our specific case.

VII. CONCLUSION AND FUTURE WORK

We have shown in this paper how Wireless Sensor Networks can be used for process control and verification in Transport and logistics processes. We identified all required components, and have presented the system requirements. As we have shown, systems fulfilling these requirements have not been devised as of today, although current research is heading in this direction.

After having identified the requirements for the proposed system, its effectiveness will still need to be evaluated. Currently, a simulation of the described system is built, and we will be testing it in the near future.

REFERENCES

[1] T. Nieberg, S. Dulman, P. Havinga, L. van Hoesel and J. Wu, Collaborative Algorithms for Communication in Wireless Sensor Networks. Ambient Intelligence: Impact on Embedded Systems, Kluwer Academic Publishers, ISBN 1-4020-7668-1, November 2003.

[2] W. Ye, J. Heidemann and D. Estrin, An Energy-Efficient MAC Protocol for Wireless Sensor Networks. 21st Annual Joint Conference of the IEEE Computer and Communications Societies(INFOCOM), Vol. 3, pp 1567-1576, June 2002.

[3] L. van Hoesel and P. Havinga, A lightweight medium access protocol (LMAC) for wireless sensor networks. In: *1st Int. Workshop on Networked Sensing Systems (INSS 2004)*, Tokyo, Japan, June 2004.

[4] J. N. Al-Karaki, A. E. Kamal, Routing techniques in wireless sensor networks: a survey. IEEE Wireless Communications Volume 11, Issue 6, pp. 6-28, Dec. 2004.

[5] D. Niculescu and B. Nath, Error Characteristics of ad hoc positioning systems. In: *Proceedings of ACM Mobihoc*, Tokyo, Japan, 2004.

[6] L. Evers, S. Dulman, and P. Havinga, A distributed precision based localization algorithm for ad-hoc networks. In: *Pervasive Computing: Second International Conference*, PERVASIVE 2004, pp. 269–286, 2004.

[7] K. Romer, The Lighthouse Location System for Smart Dust. In: *Proceedings of MobiSys 2003*: 15-30, 2003.

[8] S. Madden, J. Hellerstein, and W. Hong, TinyDB: In-Network Query Processing in TinyOS. Technical Report IRB-TR-02-014, Intel Research, Berkeley, CA, October 2002.

[9] P. Levis and D. Culler, Maté: A tiny virtual machine for sensor networks. In: *International Conference on Architectural Support for Programming Languages and Operating Systems*, San Jose, CA, USA, Oct. 2002.

[10] M. Beigl, H.W. Gellersen, and A. Schmidt, MediaCups: Experience with Design and Use of Computer-Augmented Everyday Artefacts. Computer Networks, Special Issue on Pervasive Computing, 25(4):401–409, March 200.

[11] L.E. Holmquist, F. Mattern, B. Schiele, P. Alahuhta, M. Beigl and H.-W. Gellerson, Smart-its friends: A technique for users to easily establish connections between smart artefacts, in: *Proceedings of UBICOMP 2001*, Atlanta, GA, 2001.

[12] F. Siegemund, Cooperating Smart Everyday Objects - Exploiting Heterogeneity and Pervasiveness in Smart Environments. Ph.D. Thesis, ETH Zurich, 2004.

[13] M. Strohbach, H.W. Gellersen, G. Kortuem, and C. Kray, Cooperative Artefacts: Assessing Real World Situations with Embedded Technology. In: *Proc. The international Conference on Ubiquitous Computing (UbiComp '04)*, September 2004.

[14] K. Whitehouse, C. Sharp, E. Brewer, and D. Culler, Hood: A neighbourhood abstraction for sensor networks. In: *Proc. the International Conference on Mobile Systems, Applications, and Services (MOBISYS '04)*, June 2004.

[15] M. Welsh and G. Mainland, Programming sensor networks using abstract regions. In: *Proc. the First USENIX/ACM Symposium on Networked Systems Design and Implementation (NSDI '04)*, March 2004.

[16] R. Want, A. Hopper, V. Falcao and J. Gibbons, The Active Badge Location System. In: *Proceedings of ACM Transactions on Information Systems*: 91-102, 1992.

[17] A. Harter and A. Hopper.,A Distributed location system for the active office. IEEE Network (8): 62-70, 1994.

[18] N.B. Priyantha, A. Chakraborty and H. Balakrishnan, The Cricket location-support system. In: *Proceedings of the 6th annual international conference on Mobile Computing and Networking (MobiCom'00)*: 32-43, Boston, Massachusetts, United States, ACM Press, 2000.

[19] P. Bahl and V.N. Padmanabhan. RADAR: An In-Building RF-Based User Location and Tracking System. In: *Proceedings of INFOCOM'00* (2): 775-784, 2000.

[20] D. Niculescu and B. Nath. Position and Orientation in Ad Hoc Networks. Elsevier Journal of Ad Hoc Networks(2): 133-151, 2004.

[21] Y. Shang, W. Ruml, Y. Zhang and M.P.J. Fromhers. Localization from mere connectivity. In: *Proceedings of the 4th ACM international symposium on Mobile ad hoc network & computing (MobiHoc'03)*: 201-212, Annapolis, Maryland, USA, ACM Press, 2003.

[22] D. Niculescu. Positioning in Ad Hoc Sensor Networks. IEEE Network, July/August, 2004.

[23] K. Langendoen, N. Reijers. Distributed localization in wireless sensor networks: a quantitative comparison. The International Journal of Computer and Telecommunication Networking 43 (2003) 499–518, 2003.

[24] L. Hu and D. Evans. Localization for mobile sensor networks. In: *Proceedings of the 10th annual International Conference on Mobile Computing and Networking (MobiCom'04)*, 2004.