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High Fidelity Simulation of Network Nodes with RF-Ranging Capabilities

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Abstract: We first investigate practical response of the introduced wireless sensors and then present high fidelity simulation of a promising RF-based ranging technology based on real world sampled data. Simulated devices utilize models of RF transceiver chips, which feature unique capability of providing some time of fight information. This allows to measure the raw distance between two communicating nodes in a connected wireless sensor link in a fast and efficient manner. Accordingly, range measurements allow global tracking of mobile systems like robots or the localization of nodes in a sensor network. In this context, the modeling of the device in USARSim is of interest as it allows large scale experiments without the financial and organizational burden of the real hardware. Through experiments with real world devices and their simulation also in Matlab, the fidelity of the simulated models is shown. *Copyright © 2009 IFSA.*

Keywords: Wireless sensor network, Tracking, Localization, USARSim

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1. Introduction

Spatial localization of objects is useful for an unlimited number of applications. In outdoor environments, the Global Positioning System (GPS) offers good spatial and temporal resolution [1, 2] by using small, efficient receivers [3]. But the situation is quite different indoors as well as in outdoor scenarios with limited free sky visibility, e.g., in inner cities or under trees. There, a solution is still much wanted for. This holds especially for situations where artifacts like mobile robots or sensor nodes have to be localized.

There is the whole field of Simultaneous Localization and Mapping (SLAM), which deals with the employment of local robot sensors to generate good position estimates and maps; see [4] for an overview. SLAM is also intensively studied from the multi robot perspective [5-13]. But SLAM requires high end obstacle sensors like laser range finders and it is computationally expensive.

A further set of approach tries to employ the received signal strength (RSS) as distance estimate between a wireless sender and a receiver [14-18]. If the physical signal itself can not be measured, packet loss can be used to estimate RSS [19-23]. But the relation between the RF signal strength and spatial distances is very complex as real world environments do not only consist of free space. They also include various objects that cause absorption, reflection, diffraction, and scattering of the RF signals [24-26]. The transmitted signal therefore most often reaches the receiver by more than one path, resulting in a phenomenon known as multi path fading [27, 28]. The quality of these techniques is hence very limited; the spatial resolution is restricted to about a meter and there are tremendous error rates [14, 16]. They are hence mainly suited for Context-Awareness [29], e.g., to detect who or what is in which room [14, 15, 18].

Due to the principle problems with RSS, there are attempts to develop dedicated hardware for localizing objects over medium range. This includes especially ultra sound (US) based techniques [30]. Examples are the Bat-Location-System [31] and the MIT Cricket System [32-34]. But these systems are known to suffer from the general problem of US. First of all, the speed of sound is strongly dependent from environment conditions like humidity, temperature, dust, and so on. Second, the speed of sound in air is relatively slow. The update rates of the systems are hence very low.

A promising new technology is RF transceiver chips featuring communication capability based on IEEE 802.14 for providing some time of flight information. Indeed, it allows to measure the raw distance between the two nodes in a communication link [36]. These transceivers are based on Chirp Spread Spectrum modulation, which enables them with higher robustness against multi path effects and environmental distortion. The chips operate in the 2.4GHz ISM band. They also are highly energy efficient, allowing hence the design of long running sensor nodes.

The chips have tremendous potential for localization in sensor networks or for tracking robots or people with tags that are independent of the systems they are mounted on. To be able to investigate the properties of a larger set of such nodes in a sensor network or tracking system without the burden of the related cost, deployment and maintenance, a high fidelity simulation in the Unified System for Automation and Robotics Simulation (USARSim) [42] as well as Matlab is presented here. USARSim in general provides a physical simulation, especially with realistic sensor and system data [38-41]. This should obviously also hold for our simulation of the utilized chips. For this purpose, a detailed analysis of the real world properties of a pair is made, which can be used for a high fidelity simulation of a link, which in turn can form the basis for larger networks.

2. Experimental Link Properties

In order to check the behavior of the NA5TR chip (by Nanotron) as well as defined SDS-TWR method which is a modified case of RTT, we have run some analysis on the chips' output to test whether it is in principle suitable for multi robot or sensor node localization. For this purpose, the fundamental issue of ranging was evaluated first. In doing so, an emphasis is laid on low power, indoor applications as in there, the lack of proper alternative technologies is the biggest.

Under the following experiments, the chips were evaluated operating with 1 *mW* output power. Two categories of measurements were done, both while keeping two peers in a clear *line of sight* conditions. LoS condition is the preliminary way to study the links properties, however, later on, we have addressed an approximation for more realistic condition of non-LoS. For the first level, two nodes were programmed to be able to measure the Euclidean distance of the communicating link, which was then compared against the direct ground truth distance. Of interest, for example, is the stability of the wireless modules against any multi-path fading or simple environmental distortions. The environment condition has differed slightly in the two series of experiments. In the *environment A* (which is a large hall on the campus, there is plenty of metallic materials in the construction of the building, floor and the poles. *Environment B* is an indoor basketball field, which seems to have much less metallic materials used in the construction. In both environments, measurements were taken for distances of 1 up to 40 meters, with incremental steps of 1m for ground truth. Maximum range of 40 is not necessarily the maximum of communication range of the transceivers. There were no obstacles on the communication line of sight, while there has been occasionally a human in the proximity of one or both transceivers. Results of the measurements and analysis are given graphically to provide easier comprehension.

2.1. Raw Euclidian Data

Graphs given in Figs. 1 and 2 show the raw recorded samples from the environments A and B, respectively. During the experiments, an anchor node was kept stationary while the tag node has been recording the raw distance data, and being moved in steps. For each step of 1m, the tag has also stayed stationary recording samples in a time window of 60 seconds. Both nodes always were kept in the height of 50 cm from the floor. Different time windows are shown in both Figs. to give a rough qualitative idea of typical measurement fluctuations. The most noticeable feature of all recordings is that there are often considerable jumps in the beginning and the end of the trend. It is considered to be due to the effect of the human body on the 2.4 GHz ISM band signal.

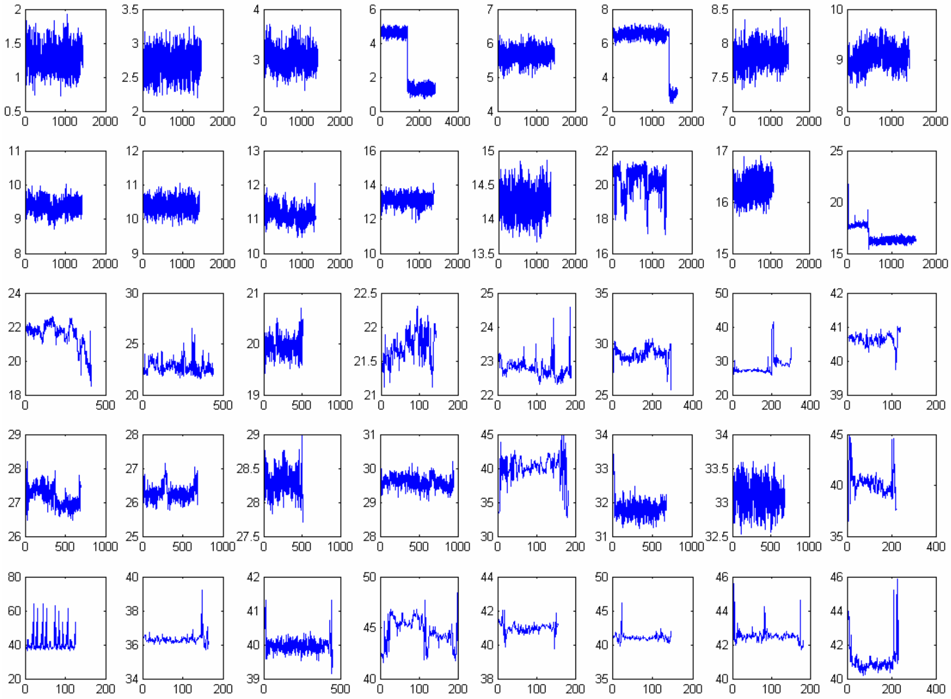


Fig. 1. Recorded raw distances are shown in these graphs for environment A. Each sub-graph is to be associated with 1m increase of the linear distance between the peers. y-axis shows measured ranges while x-axis indicates number of recorded samples; different time windows are shown to give a qualitative idea of measured fluctuations in the raw RTT data.

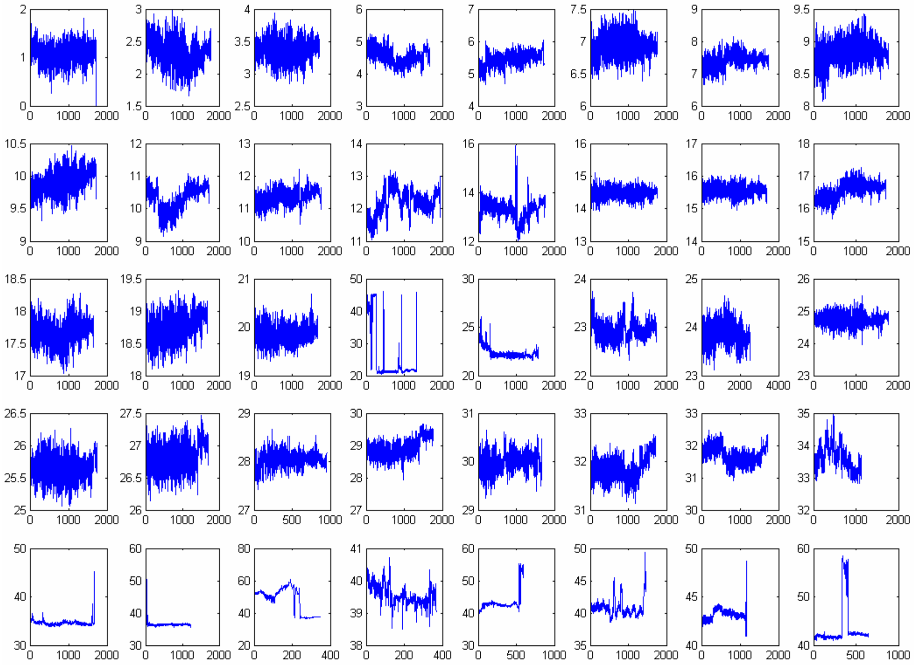


Fig. 2. Recorded raw distances are shown in these graphs for environment B. Each Sub-graph is to be associated with 1m increase of the linear distance between the peers. y-axis shows again measured ranges while x-axis indicates number of recorded samples.

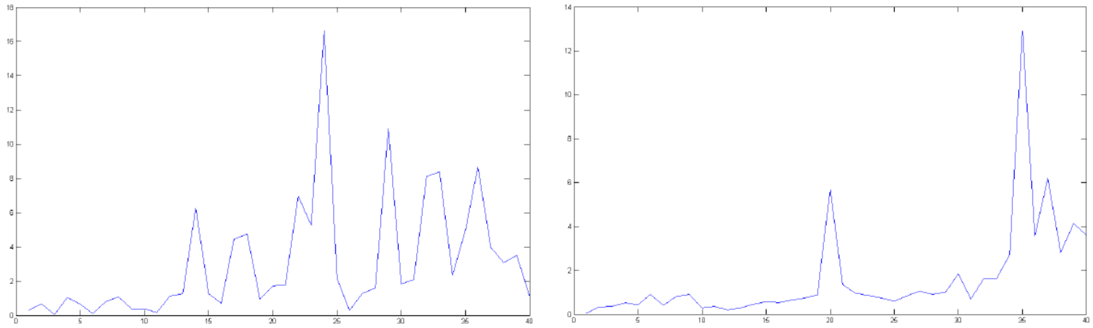
2.2. Measurement Calibration

The distance error here is defined as the difference of average value of each recorded raw data set (for each 1 m distance interval) with respects to its known corresponding ground truth. It can be seen that there is a linear relation between measured and actual distances. Furthermore, there is an almost linear increase in the maximum and minimum outliers of the error when distance is being increased. In environment B, the increase trend is much smoother while in the graph associated with environment A, there are wild behaviors which clearly are due to the environmental effects on the radio signal.

Computation of the range measurements can be improved with a slight calibration factor. As shown in Figs. 3(a) and 3(b), the error tends to slightly increase with raw distance. Furthermore, there can be relatively large fluctuations in the error as also shown in Figs. 3(a) and 3(b) whereas the shown range measurements is simply averaged over their respective data set. An alternative filter is to compute the Median, which is more robust against rare but still large outliers. The disadvantages of the Median in return are; it is *a)* computationally more expensive and *b)* highly non linear and less suited for formally derived analytical methods. Nevertheless, the Median provides a good alternative to the Average, especially when only few range samples are measured.

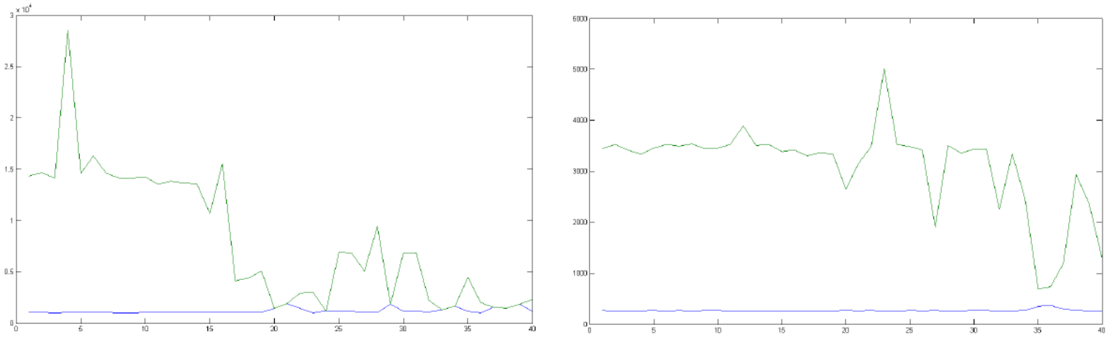
2.3. Packet Loss

An analysis of the number of valid packets shows that the packet loss rate is increasing with respect to the distance increment. For both environments, communication packets were recorded for 60 seconds time frames for each data set. Figs. 4(a) and 4(b) show that packet loss has clearly starting to be noticeable for distances of larger than 16m. It is to be emphasized that transceivers are working with transmission power as low as 1 mW for all reported results. Compared with environment B, there are less packets received in general with respect to environment A (123,523 in total, against 327,290), however there is a dramatic drop for longer distances in the second environment. It is to be noted that for keeping a balance in the processed data, a normalized number of recorded samples are processed to have a unique scale for comparison. Smooth lines in graphs 4(a) and 4(b) show the number of processed samples which are in total 47,324 for environment A versus 10,611 for environment B.



(a) environment A　　(b) environment B

Fig. 3. The average of the error is significantly fluctuating in environment *A*. The average of the error is generally rather smooth (except in some few sample sets) in environment *B*.



(a) environment A　　(b) environment B

Fig. 4. Smoothed line is normalized number of processed packets out of the received valid data. The other line (with more fluctuations) shows the overall number of received packets. For both environments, it drops significantly once internode distance is increased.

2.4. Distribution Fit of the Real Data

Figs. 5 and 6 show distribution of the measured values for different ground truth points. Discarding the limited number of different shapes, these graphs confirm that population distribution of the recorded data is fitting into a Gaussian distribution model. This property is the main concern when modeling the ranging capability of the nodes in the simulations.

2.5. Interpretation of the Mean Value

As mentioned before, the mean value of the measured ranges is almost linearly increasing when enlarging the ground truth distance. It however can be seen that the mean values are ascending much more smoothly for environment B (Fig.7(b)), because for higher distances the minimum and maximum recorded values in the other environment are more often out of range (Fig. 7(a)).

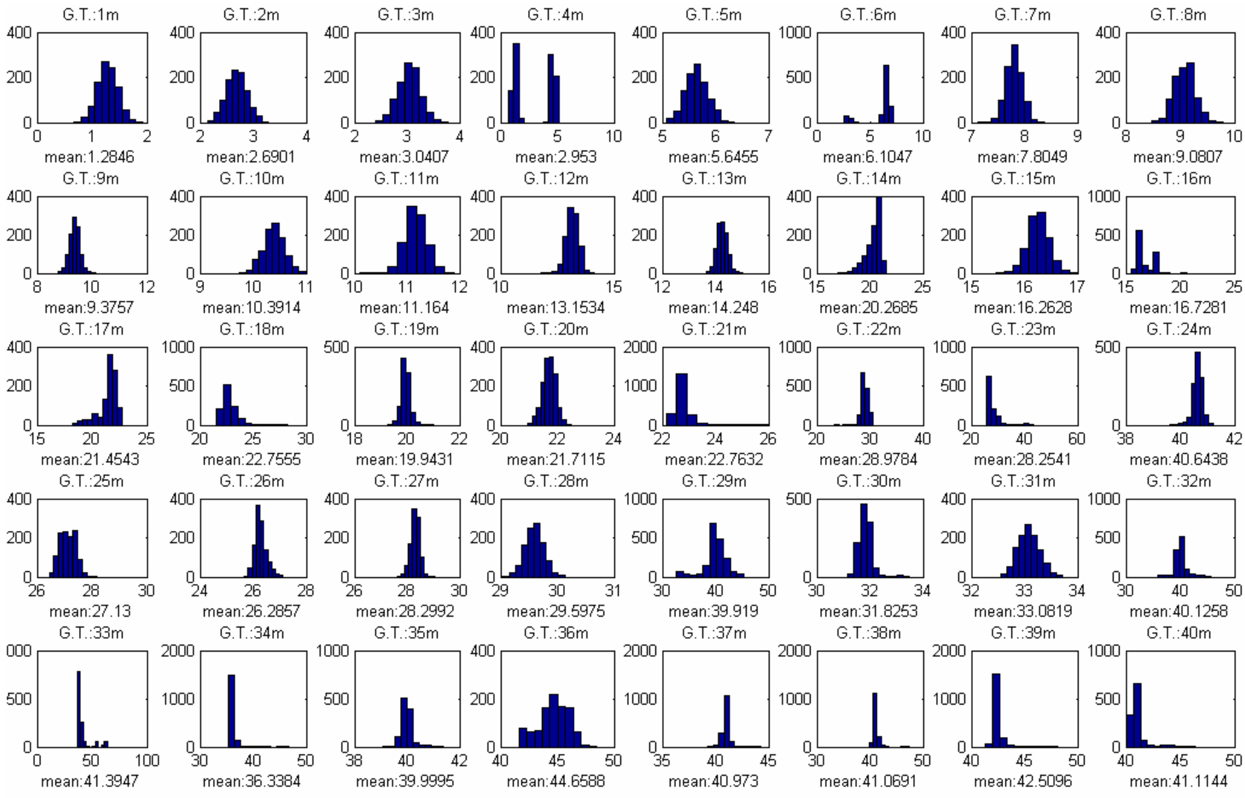


Fig. 5. Population distribution of the recorded data for environment A. It is observed that almost all can be roughly represented by a Gaussian _t. Each subgraph is to be associated with 1m increase of the Euclidian distance between the peers. "G.T" on top of each subgraph denotes the *ground truth distance*, and "mean" beneath of each, indicates the mean value of the corresponding population.

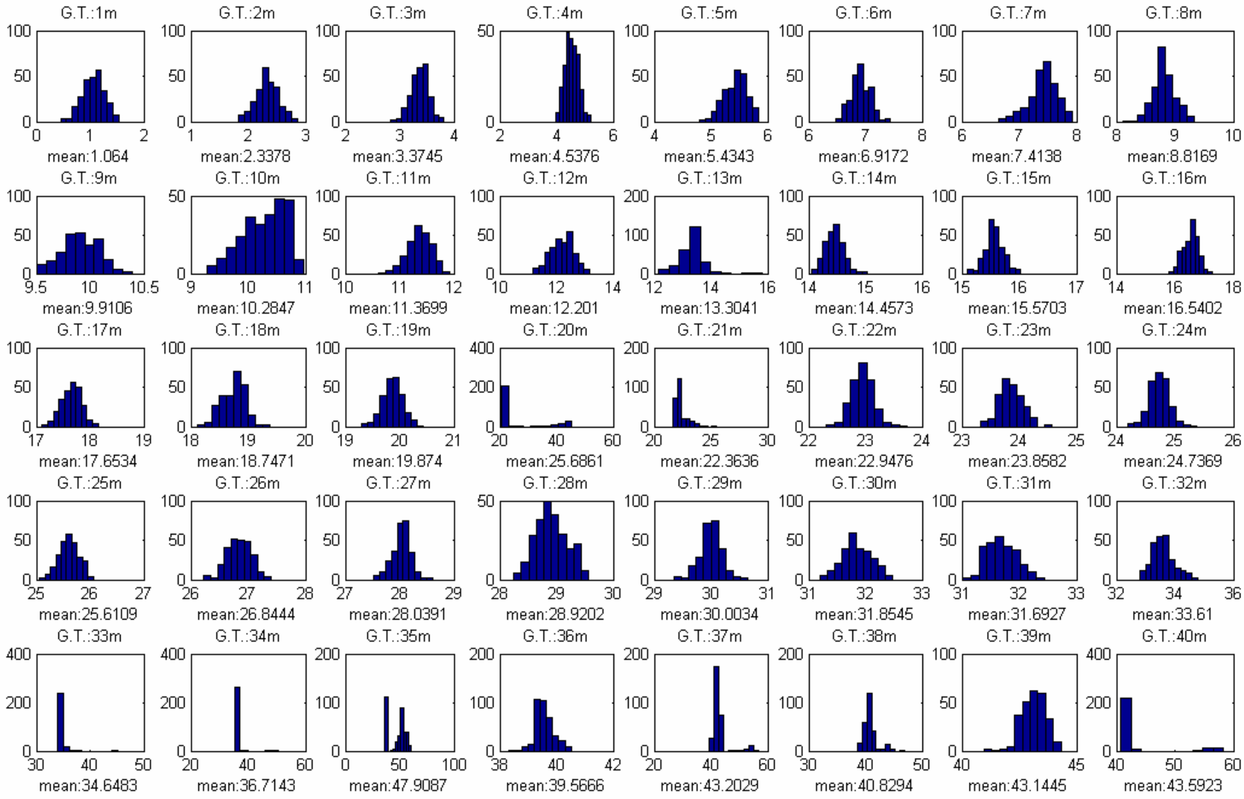
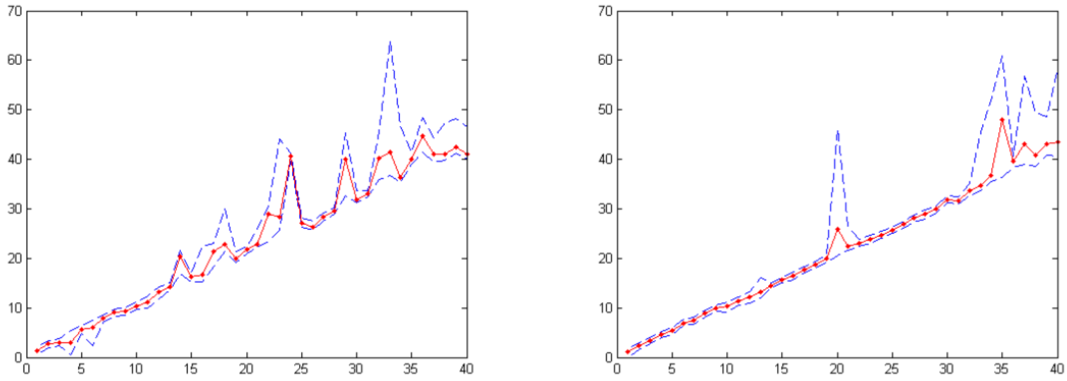


Fig. 6. Population distribution of the recorded data for environment B.

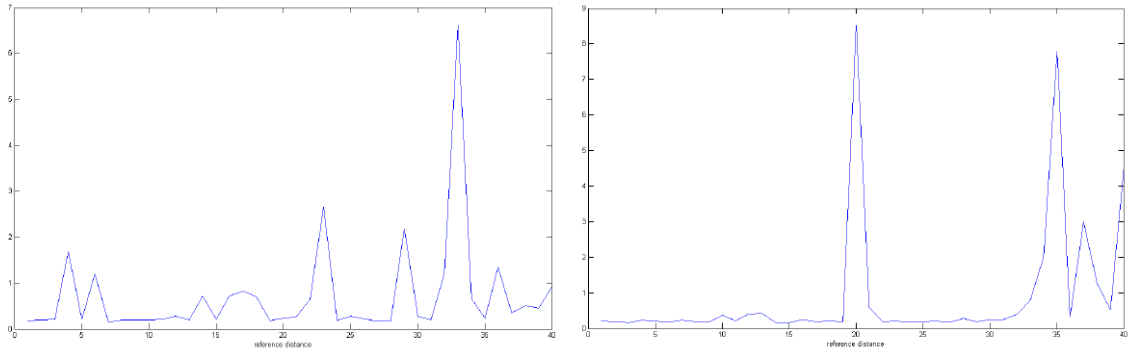


(a) environment A (b) environment B

Fig. 7. The red line shows the mean values of the measured distances. The blue lines show the maximum and minimum outliers in the measurements.

2.6. Standard Deviation of Ranges

Standard deviations of the recorded data sets with Gaussian distribution are given in graphs Fig. 8(a) and 8(b). There, in environment A, average of the standard deviation value is higher (0.7042 m) while having some unpredictable jumps. For the other environment, B, average value of the standard deviation of the Gaussianly distributed data is 0.2393 m (outlier distances 20 m and 34 m are discarded).



(a) environment A (b) environment B

Fig. 8. Standard deviation of normally distributed raw data: In environment A, there are unpredictable jumps which can indicate lower level of reliability of raw range. In environment B, there is seen a rather constant trend for measured raw range values, mostly staying around 23cm. This, apparently, is the most environmental dependent factor for the ranging modeling.

3. USARSim Ranging Model of the Transceiver Nodes

Based on the real model of the transceiver nodes, they are simulated in the USARSim environment such that can be used for ranging and indeed localization. Using raw ranges for localization is explained elsewhere in more details, where we have shown how Multidimensional Scaling Methods can practically be used for building a positioning scheme in a mobile network of real robots equipped with the aforementioned wireless nodes [43]. In the USARSim, communication model considers a pair link in order to follow the real world data and experiments described then in section 2. The most important aspect is that the real world experiments show that error in the RF ranging can be fitted in Gaussian representation.

The model of the transceiver that is used in the USARSim simulations can be seen in Fig. 9. Snapshots of Fig. 10 show indoor and outdoor deployment of the nodes, on static as well as dynamic robotic platforms. The most important requirements for the modeling definitions of the wireless nodes are the followings:

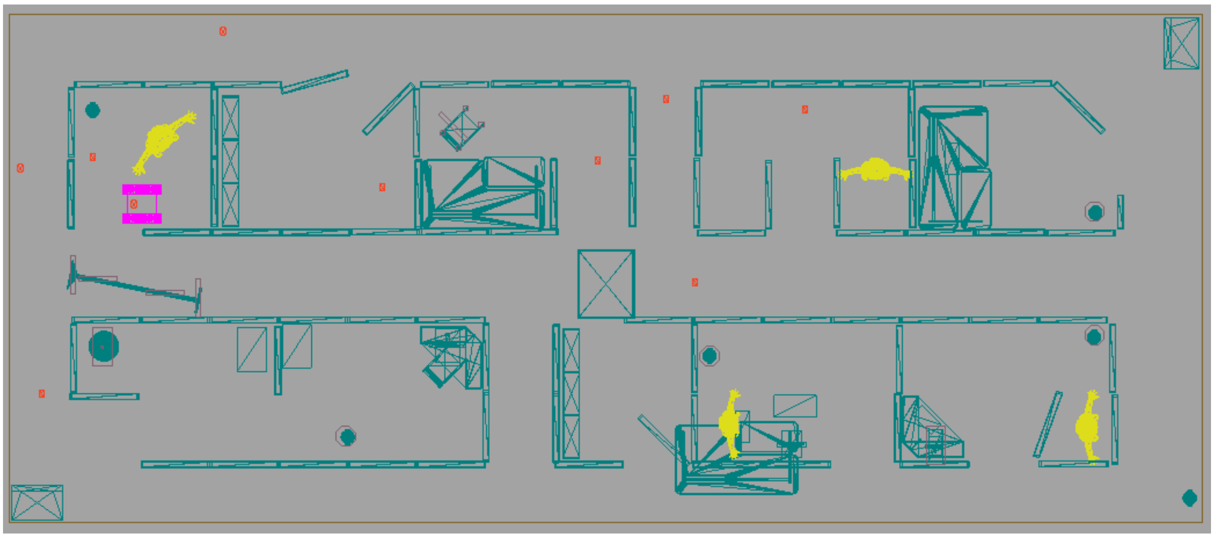
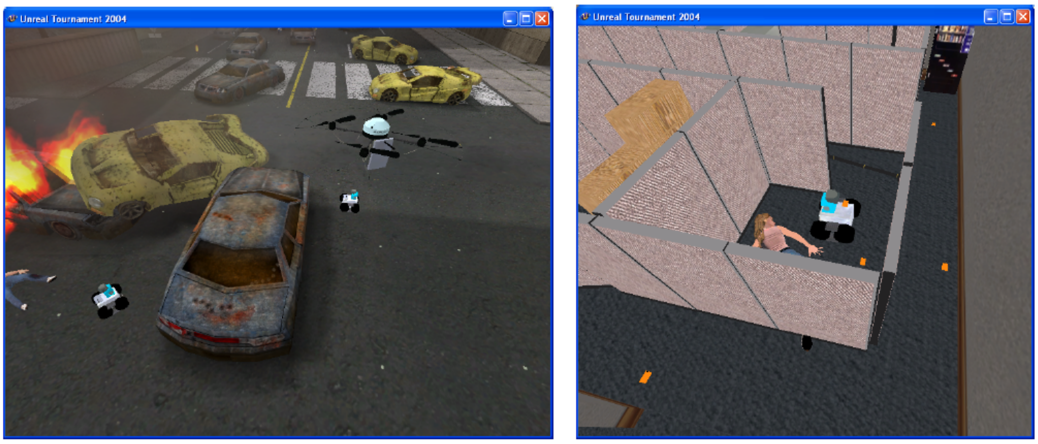


Fig. 9. Static mesh model of the module in USARSim environment for an indoor scenario. Obstacles are in green, floating wireless nodes in orange, mobile robot carrying a node in pink and human in yellow.



(a) Outdoor scenario (b) Indoor scenario

Fig. 10. Snapshots of the modeled nodes in the USARSim environments for both outdoor and indoor situations. Dynamic nodes (modules installed on mobile robots) as well as the static ones can be covered in the simulated environments.

1. *Uniquely Identifiable* - Each module must have a unique ID so as to enable its peer ranging and indeed position to be calculated individually. This is done by giving an integer ID to each node, when it is added to the environment.

2. Deployable to the environment - Each node must be easily place-able in the environment. The chip class can easily be added to the map and placed in any position prior to running the simulation. They can also be added dynamically by the robot during the simulation (thereby simulating the action of the robot dropping the sensor nodes in the environment using an actuator). This capability can be used when marking a location in the environment is desired.

3. Attachable on the robot - It should be possible to place a sensor node on the robots as well. This allows us to localize the robot on the sensor network. This requirement is also met in order to make the USARSim model build both static and dynamic wireless sensor network.

4. Communicability - Each node should be able to locate the other sensor nodes of the network within a certain range. That also concerns the unique addressing of the transceivers. If nodes are placed/dropped in distances not larger than maximum of the communication range, that implies a connected graph representing the whole network, and indeed a clear positioning of all nodes for any arbitrary module in the network.

3.1. Modeling of the Sensor's Observation

As stated previously, sensor nodes are able to communicate with each other within a certain range. As a result of this communication, they can calculate their distance to other sensor nodes in the network. This value is dependent on the ground truth distance between them (for both dynamic and static nodes). It is to be taken into account this data is noisy due to environmental disturbance on the radio signal. In section 2, it was seen that the noise embedded in the sensor measurements can be considered as a Gaussian variable. Due to this fact, the wireless module's observation in the USARSim is calculated using the simple steps below:

1. *At each time step, find all sensor nodes within the designated range, and respectively their ground truth positions using the simulator engine;*
2. *Calculate the Euclidian distances for those nodes;*
3. *Embed the defined Gaussian noise to the pure values based on the real world data model (adjustable mean and standard deviation);*
4. *Report the noisy range values.*

4. Scalability and Stability

In order to study the behavior of the solution in a larger scale network using the algorithm given in [43], realized model of the hardware was implemented in Matlab, giving the feasibility of testing any arbitrary network configuration independent from its size. At the same time, this investigation is significantly useful because it concerns the uncertainty of the Gaussian fit of the measurements in terms of noise influence. This influence mainly comes as a matter of environmental distortion as well as obstacles blocking the lone of sight. In the simulation experiments, Horn's Algorithm ([44]) was used for measuring the accuracy of the retrieved positions compared with the ground truth positions. Network size (i.e. number of nodes in the network) has varied between 5 and 60. For each set of network size, data sets are averaged over 20 randomly generated configuration spaces in a work space of 300x300 squared meters. Actual measures were polluted with Gaussian noise, zero mean and standard deviation varying between 0.0 to 2.4 meters (0.3m intervals). In total, 1,920 random configuration spaces were processed. Seen in the trends shown in Fig. 11, growth of positioning error when Gaussian noise pollutes the measurements, interestingly degrades when size of the network gets larger. This inherently confirms that optimizations (which are used in multidimensional scaling solution) have capability of dealing with noisy conditions and larger sizes for networks.

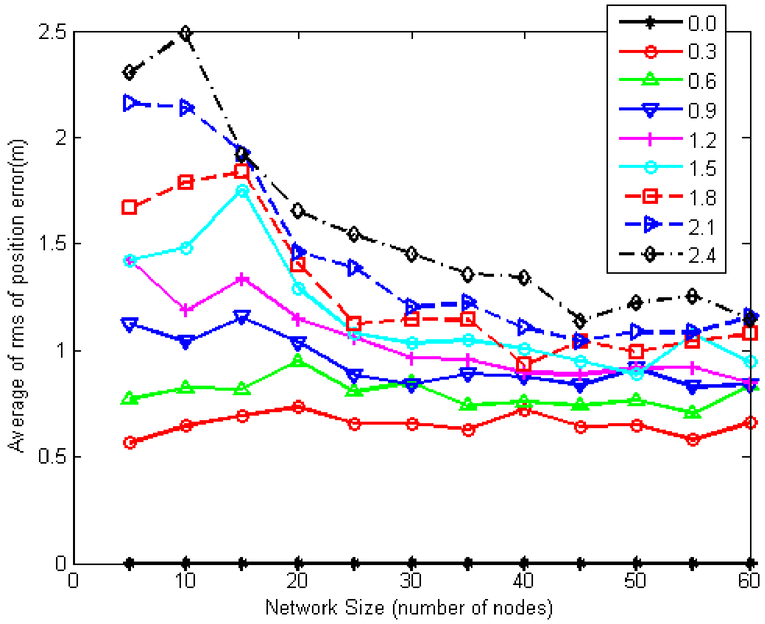


Fig. 11. Positioning error of the simulated networks of size up to 60 nodes within a work space of size 300x300 squared meters. Large size network seems more stable against noisy measurements whereas a network of size 60 seems twice more accurately localized than a network of size 5 under the same noise condition (standard deviation of 2.4 m).

5 Conclusions

In order to have a more realistic model of the wireless modules added in the simulations of USARSim, there were carried out plenty of experiments for recording enough real world data in order to get a more comprehensive and accurate representation of the modules and their behavior under different environmental conditions. Having such a high fidelity capability of simulation of the models, eases both qualitative and quantitive assessment of the network in an unreal world under very realistic conditions. USARSim provides standard testing platform to that ranging and localization enabled nodes, for a mode effective design. Having such sensors in the simulated environment can be used in both cases of either having a dynamic or static wireless sensor network; a network of which each node can get realistic ranges to all other nodes and be aware of their respective locations. These characteristics are of interest especially because they can be used in evolutionary building a non-existing localization, for example when a mobile robot drops wireless nodes randomly in the environment and the network initiates the actual position of the nodes. This also is interesting when a position in the environment is required to be marked with a location tag.

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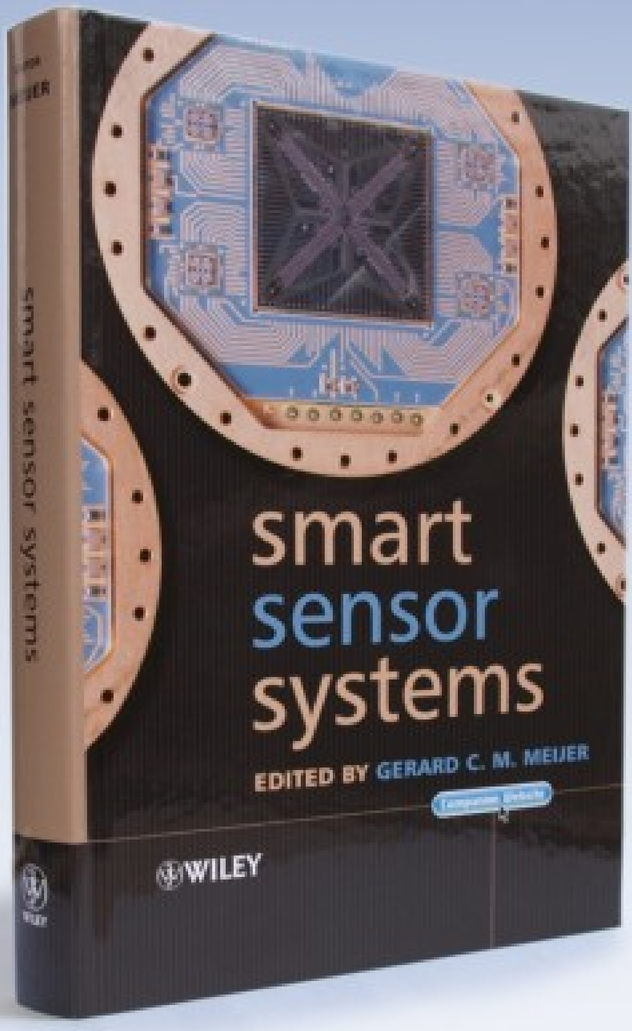
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