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A Study on Localization in Wireless Sensor Networks using Frequency Diversity for Mitigating Multipath Effects

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***Abstract*—Self-localization capability is for many ad-hoc network deployments an essential feature. Unfortunately, the radio environment introduces a several phenomenons which negatively influence the accuracy of the localization. In this paper we investigate the effect of multipath propagation in outdoor environment on accuracy of localization and propose a method using frequency diversity for RSS measurement in order to mitigate the fading caused by multipath propagation. To that end, a localization algorithm based on least square minimization of measured distance and weighted centroid algorithm are used to verify the frequency diversity concept. The results of simulations and measurements are presented also with the relation to an antenna height.**

***Index Terms*—Localization, Ad-hoc, WSN, frequency diversity.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) is a modern technology gaining recently its significant success since a broad application use. Accurate and low-cost sensor localization is a critical requirement for the deployment of wireless sensor nodes and RFID devices in a wide variety of applications.

Different localization techniques have been proposed (overview for instance in [1]) and are based on the measurement of the time of arrival (TOA), the angle of arrival (AOA) or the received signal strength (RSS). From these measurements, the position of the node can be determined using different localization algorithms. In practice, RSS is defined as a voltage measured by a receiver's received signal strength indicator (RSSI) circuit. Often, RSS is equivalently reported as measured power. Wireless sensor nodes communicate with each other, thus, the RSS can be measured by each receiver during data communication without additional bandwidth utilization or energy requirements. For these reasons, this paper will focus on RSS-based localization techniques.

Localization accuracy is influenced by several factors, such as manufacturing tolerances, antenna inadequacies and, most importantly, multipath. The effect of multipath is often difficult to predict or mitigate, although multipath is expected to be significantly stronger indoors than outdoors. Some of the RSS-based methods require a relationship between the distance and the received power to estimate the position of unknown devices [2]. This relationship can be obtained using a channel model or using a database with recorded RSS maps [3].

In this paper we investigate the possibility of using frequency diversity for position estimation in outdoor scenarios. The multipath propagation and large fading have a significant negative effect on the accuracy of position. Therefore, we propose to use two uncorrelated frequency channels for RSS measurement. Using two frequencies with a span larger than coherence bandwidth we will be able to avoid the negative effect of fading points. Considering that RSS measurement falls for one frequency into the fading point (local minimum), the measurement with the other uncorrelated frequency will be in local maximum. To show the advantage of frequency diversity we perform several simulations and measurements with various antenna heights.

Following section presents a flat earth model for channel modeling in order to understand multipath shadowing effects. Section Localization in WSN discusses localization algorithms and presents two of them used further in the work to evaluate influence of frequency diversity. Next section presents simulation and experimental results, investigates the viability and influence of using frequency diversity on the accuracy of position estimation. Finally, the last section concludes the paper.

II. SIGNAL PROPAGATION

Several localization algorithms establish the relationship between the distance and the received power in order to estimate the position of unknown devices e.g. [2], [3]. In WSN propagation, the influence of reflections in the environment must be considered. Path power loss can be modelled as the sum of several waves reflected in the ground, walls or other objects. Thus

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$$L_p = -10\log\left(\frac{\lambda}{4\pi}\right)^2 - \\ -20\log\left(\frac{1}{r_0}e^{-jkr_0} + \sum_{i=1}^{N}\Gamma_i\sqrt{t_i}\,\frac{1}{r_i}e^{-jkr_i}\right), \qquad (1)$$

where λ is the wavelength, r_0 is the length of the direct path, r_i the length of the i-th reflected ray path, N the total number of reflections, k the wave number, and j is the complex number $\sqrt{-1}$. The antenna's gain when transmitting depends on the direction. To account for this, t_i is the normalized antenna radiation pattern and Γ_i is Fresnel's reflection coefficient in the object for the i-th wave, as given by [6]. Thus

$$\Gamma_i = \frac{\cos\theta_i - q\sqrt{\varepsilon_c - \sin^2\theta_i}}{\cos\theta_i + q\sqrt{\varepsilon_c - \sin^2\theta_i}}, \qquad (2)$$

where ε_c is the complex permittivity of the ground, θ_i is the incident angle with the normal to the ground and q is a polarization-dependent factor, which is q=1 for horizontal polarization and $q=1/\varepsilon_c$ for vertical polarization.

When only the direct path is considered, model (1) reduces to the free-space Friis model. Another simple model consists of only taking into account the direct ray and the reflection in the ground [6], assuming the flat-earth model (N=1). For typical earth parameters (relative permittivity ε_r = 15 and conductivity σ_c = 0.005 S/m) and typical antenna heights (between 1-2 m), Fresnel's reflection coefficient Γ_i is almost real and the worst case is when Γ_i = -1. Note that when the distance between nodes r is larger than antenna height h_1, h_2 ($r >> 4h_1h_2/\lambda$), equation (1) can be simplified as follows

$$L_p = -10\log\left[\left(\frac{h_1h_2}{r^2}\right)^2\left(\frac{\sin\frac{2\pi}{\lambda}\frac{h_1h_2}{r^2}}{\frac{2\pi}{\lambda}\frac{h_1h_2}{r^2}}\right)\right] \approx \\ \approx -10\log\left[\frac{(h_1h_2)^2}{r^4}\right]. \qquad (3)$$

Under these assumptions, the slope of the path loss versus the distance is equal to n=4 (40 dB per decade). In WSN environments these assumptions are not true, because the distance is closer than the turn-on distance R_0, and the path loss exponent could differ from the free space case (n=2) and the flat earth case (n=4). In waveguide-like environments where waves only propagate in one direction (rooms, pipes, tunnels, etc.), the path loss can behave exponentially with distance due to the modal nature of propagation and may be smaller than in free space until a certain distance from the transmitter where the two become comparable.

An empirical model is often used in WSN environments and is based on a two-slope model [7], [8]:

$$L_p(dB) = -20\log\left(\frac{\lambda}{4\pi}\right) + n_1 10\log(r) + \\ + (n_2 - n_1)10\log\left(1 + \frac{r}{R_0}\right) + L_{obs}(dB), \qquad (4)$$

where L_p is the propagation attenuation in dB, n_1 is the path loss factor for distances shorter than R_0, and n_2 is the path loss factor for distances longer than R_0 (for the flat earth model n_2 =4). L_{obs} is the loss due to diffraction and medium attenuation. In practice, for WSN, R_0 is longer than the maximum cover range. Thus, model (4) can be simplified by taking into account only the first path loss term $n_1 10\log(r)$.

In performed simulations (Section Simulation and measurement results) we use the flat earth model described by (1) in the frequency range 2.4 GHz ISM.

III. LOCALIZATION IN WSN

A reliable positioning system is critical in many WSN applications, especially for mobile ad/hoc networks. The positioning system must have the following features: i) adequately accurate (the required accuracy always depends on the specific application); ii) real time (since the location information, it should be updated periodically at appropriate intervals); iii) low complexity (it is expected that positioning should be done as an additional function of the devices along with their routines, as for instance, access points and environmental sensors). Therefore, system complexity is constrained by power and computational capacity of the available devices.

Several positioning algorithms focus on different types of data explored [8]. As addressed before, the main techniques are based on Angle-of-Arrival (AoA), Time-of-Arrival (ToA), and the radio signal strength, which is mostly indicated by the RSSI. Earlier studies have shown that a sufficient accuracy could be achieved in finding the range using AoA and ToA-based techniques. Recently, additional improvements have been obtained using Ultra Wide Band (UWB) technologies with ToA measurements [10], [11] or using AoA-assisted ToA systems [12]. However, these systems require extra hardware support, such as antenna arrays or UWB transceivers to measure the ToA between the devices. In consequence, it increases the complexity of the devices and, in addition, today UWB devices are too expensive. On the other hand, GPS is a well-proven technique and it is usually very effective for outdoor positioning. However, GPS is not suitable for indoor positioning due to interference and multi-path fading.

From studies on radio propagation models, such as the one presented before or others in the literature, it has been shown that the received signal strength is essentially related to the transmission distance. In consequence, several works on localization systems use the radio signal strength. Moreover, most signal strength-based indoor positioning systems have been proposed to make use of the existing indoor networking facilities, such as WLAN systems, RFID Tags and, especially, WSN.

After deploying the sensor network over an area of interest, the sensor nodes with known position are called beacons or anchors. All other nodes in the network without known positions are called unknowns. The localization process starts when the RSS between the beacons and unknowns has been determined. Several positioning algorithms differing in many aspects have been proposed [13]–[19]. Ranging-free and ranging-based algorithms is one categorization which can be used. In order to investigate the dual frequency effect on positioning accuracy we choose one algorithm from each category to proof the concept.

Least square method belongs to range-based algorithms which means that it uses a distances between nodes to estimate position of the unknowns. Distances can be obtained from several measurements methods presented previously but we focus on RSS method as previously indicated. Least square method is based on the hyperbolic positioning algorithm [2], which reduces the positioning problem to a linear least-square problem. Once the distances between the unknown and the anchor nodes have been estimated by inverting the propagation model, the position of the unknown node can be calculated using the algorithm.

Weighted centroid localization algorithm is a representative of the second class known also as approximated algorithms [4], [5]. In contrast with algorithms based on the least squared method, these algorithms avoid determining distance in their approach. Consequently, a signal propagation model is not needed. Regarding the energy constraints in sensor networks, these approximated algorithms consume less power but their position estimates can contain higher localization errors.

After all positions of the anchor nodes have been determined, the approximate position of the unknowns *(x,y)* is estimated by a weighted centroid determination where the weight is based on a received power.

IV. SIMULATION AND MEASUREMENT RESULTS

Fig. 1 compares the simulated path loss on the flat earth model using (1)-(2) with typical terrain characteristics at the 2.45 GHz ISM frequency band that is frequently used in WSN and active RFID (RF identification). Four antenna heights have been studied (0.15 m, 0.5 m, 1 m and 2 m) for the transmitter and receiver antennas in both cases. Only vertical polarization is considered since, in practice, dual-polarization antennas are not usually used in WSN such as Zigbee networks or active RFID.

From these simulations (Fig.1), it is clear that a simple one-slope model works better for low antenna heights and large ranges. The number of fadings and their attenuation increase for low distances. From this point of view it is better to use low antenna heights for localization purposes which is rather typical in WSN applications. However the attenuation increases due to partial cancellation between direct and reflected paths, thus, the receiver power is quicker in reaching the receiver sensitivity (typically between -85 dBm to -90 dBm depending on the model and band) than when a higher antenna height is used. Consequently, there is a compromise between the maximum range and the antenna height. Another effect of the interference between paths is that the positions of the fadings are separated at approximately half-wavelength for small incidence angles. Thus, the problems caused by multipath increase in the 2.45 GHz ISM band; however, this band is more interesting for communication purposes (such as Zigbee) than are lower ISM bands because of the larger bandwidth available. In addition, for longer distances, more paths (for example reflection from walls) could explain certain large fadings that take place at about 4 m.

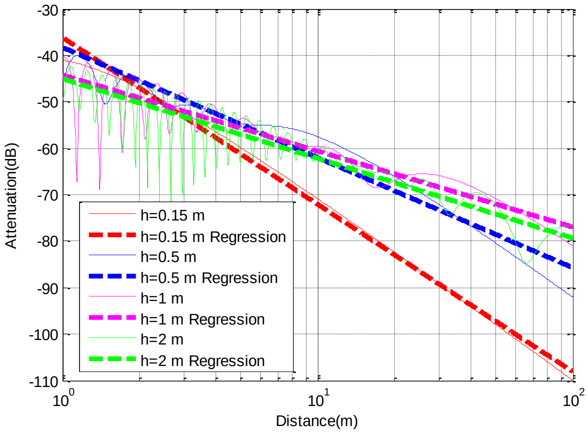

Fig. 1. Simulated path loss as a function of distance at 2.45 GHz.

Although, a flat-earth model may be suitable for outdoor systems, it is too simple for indoor systems because it does not take into account other reflections. Nevertheless, despite these limitations, the flat-earth model can help to understand some trends. In order to compare with theory, some measurements in the 2.45 GHz ISM band are also presented in Fig. 2 for five antenna heights. In order to get platform independent investigation results a microwave signal generator is used to generate a continuous wave signal of -10 dBm. The power of the received signal is measured with a spectrum analyser (Rohde&Schwarz FSP3) with a low-noise amplifier connected at its input (Minicircuits ZX60-3011) to improve the receiver sensitivity. Omnidirectional monopole antennas are used in both, the transmitter and receiver.

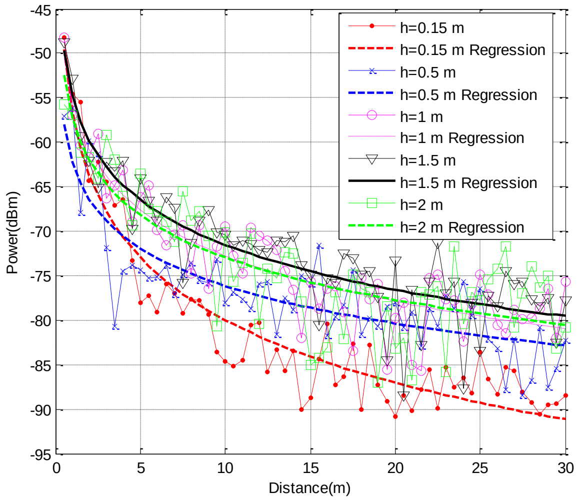

Fig. 2. Measured received power as a function of distance at 2.45 GHz.

Since the fading amplitude is frequency dependent, the maximum and minimum positions depend on the polarization (for a given frequency band). Thus, polarization diversity can be effectively used to combat multipath channel fading. However, polarization diversity is not often used in WSN. Another idea is to use frequency diversity to combat multipath. Several frequency channels are usually available in WSN (16 channels in 2.4 GHz ISM band [20]); if the frequency spacing used for RSS measurement is larger than the coherence bandwidth of the channel, these measurements are uncorrelated [8]. The coherence bandwidth determines the correlation between two frequency components, and is related to small-scale fading effects. However, shadowing is a large-scale fading effect, and RSS measurements are commonly averaged over to remove the effects of small-scale fading. The idea is to investigate the possibility of using two or more frequencies to mitigate fading effects. In this case, we expect that, if the power received at one frequency falls in a minimum, then it will fall in a maximum position for the other frequency. To ensure this point, the frequency spacing should be greater than the coherence bandwidth of the channel, which is in general dependent of the scenario. To show the effect, the frequencies for the measurement have been chosen from the beginning and the end of the 2.45 GHZ ISM band (1st and 16th channel). In Fig. 3 the path loss is simulated for two frequencies separated by 80 MHz (2.40 and 2.48 GHz). This simulation shows that frequency diversity can successfully work for small distances; however, for larger distances, the incidence angle increases and the two paths are almost in phase, with similar delays, and little difference is observed in the power received at the two frequencies.

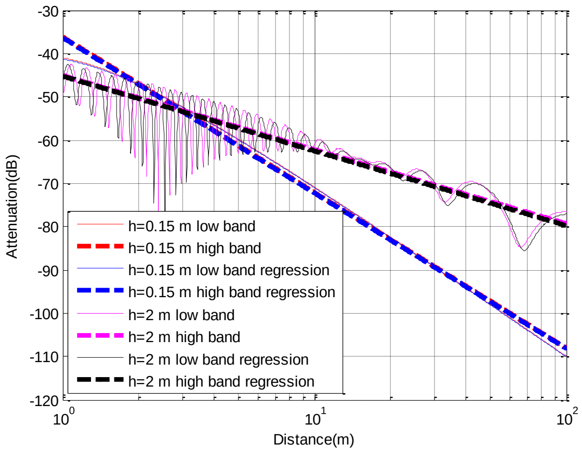

Fig. 3. Simulated path loss as a function of distance for two frequencies separated by 80 MHz in the 2.45 GHz ISM band.

Fig. 4 gives the measured received power at the two frequencies as a function of distance, which shows that the difference between the two bands is small for low antennas and increases as the antenna height increases. The positions of fadings between the two frequencies are also different and show a certain lack of correlation between frequencies for high antenna heights. To conclude, frequency diversity can be effectively used to combat multipath channel fading for high antenna heights and the typical cover ranges in WSN. For low ISM bands (867 MHz), frequency diversity is difficult to apply because of the small frequency band used.

Another conclusion is that although the flat earth model can explain some channel effects, more paths (for example reflection from walls) may explain the large fadings for longer distances. Finally, systematic outliers based on channel effects are also noticeable. These outliers may be caused by reflections from the ground or walls and are highly dependent on antenna height.

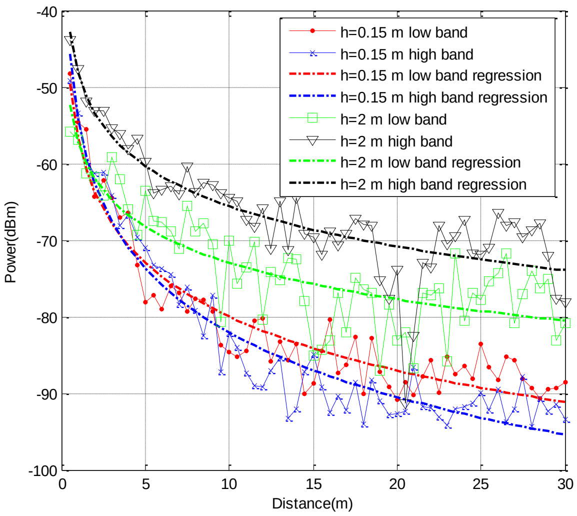

Fig. 4. Measured received power as a function of distance for two frequencies separated by 80 MHz in the 2.45 GHz ISM band.

To determine the influence of the antenna height and the possibility of improving the localization by means of frequency diversity, the following figures show the localization error as a function of the mobile node position (x,y) using four anchors placed in the vertexes of a 16x16m square. In order to evaluate these errors, some simulations have been done. As the anchors coordinates are known, for a given point, the Euclidean distance to each anchor is computed. Then, the received power or RSS is calculated interpolating the measurements at each frequency for the specific antenna height and frequency (Fig. 2 and Fig. 4). These measurements were done for an outdoor scenario. Then, an estimation of the position is obtained using the LS or centroid algorithm. Finally, the localization error is calculated as the distance between the real and estimated position. In a single frequency case, only the RSS obtained from measurements at this frequency are used. In case of frequency diversity, the average RSS between the two frequencies are used as input to the localization algorithms. The procedure is repeated for each point in the analyzed area.

Fig. 5 and Fig. 6 are obtained with least square and centroid algorithms, respectively, using a single frequency and an antenna height of 0.5m. A significant improvement is obtained when the same cases are analyzed using instead the mean RSS computed with two frequencies, separated by 80 MHz within the 2.45 GHz ISM band, (Fig. 7 and Fig. 8).

The results for 0.5 m and 2 m antenna heights are summarized in Fig. 9, which shows the cumulative probability of error obtained using both algorithms. The error is significantly higher than when the antenna is low because of the significant fading, as can be seen in the measurement range in Fig. 2 and Fig. 3. For the high antenna case, using frequency diversity with the least square algorithm did not improve the results, in contrast with the weighted centroid method, which proved to be very robust with high antennas. This robustness against NLOS and multipath effect can be seen in Fig. 9.

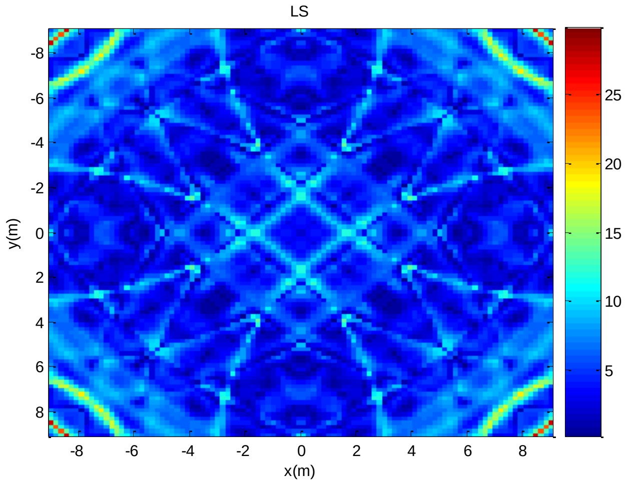

Fig. 5. Simulated error using the least square algorithm with a single frequency in the 2.45 GHz ISM band and an antenna height 0.5m.

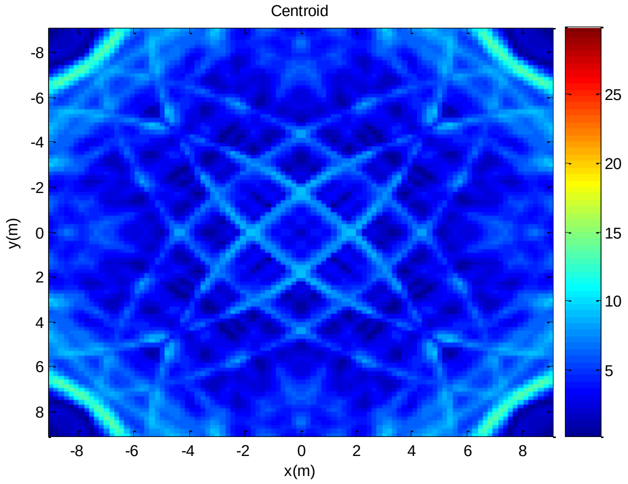

Fig. 6. Simulated error using the weighted centroid algorithm with a single frequency in the 2.45 GHz ISM band and an antenna height 0.5m.

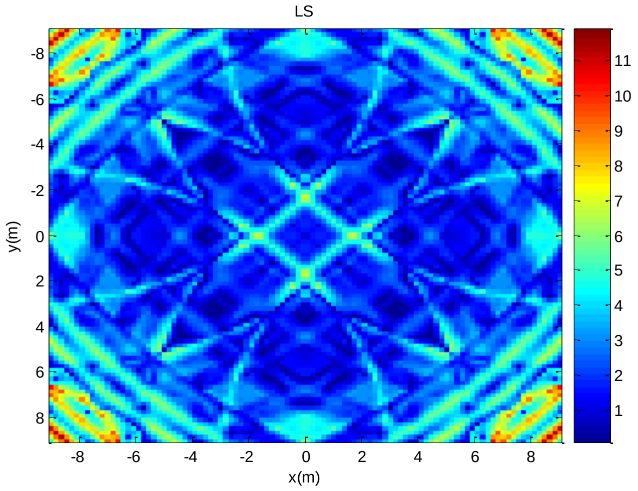

Fig. 7. Simulated error using the least square algorithm with frequency diversity in the 2.45 GHz ISM band and antenna height 0.5m.

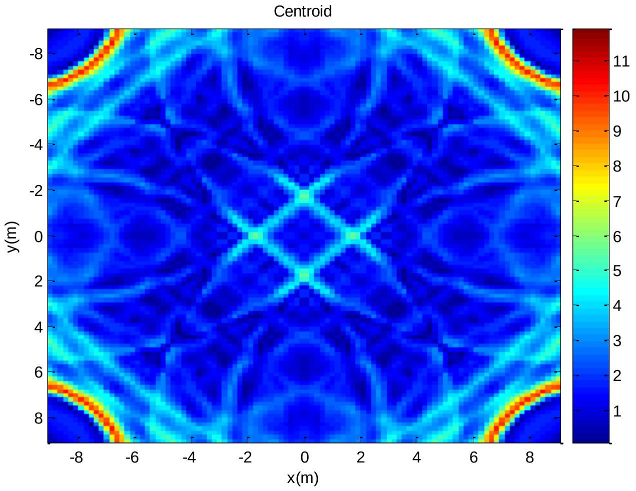

Fig. 8. Simulated error using the weighted centroid algorithm with frequency diversity in the 2.45 GHz ISM band and antenna height 0.5m.

Fig. 9 also shows the probability for the case where the anchor that it is located at (-8,8) m is affected by a shadowing of 10 dB due to an obstacle. In this case the weighted centroid algorithm with frequency diversity in the 2.45 GHz ISM band was used, and the antenna height was 2 m.

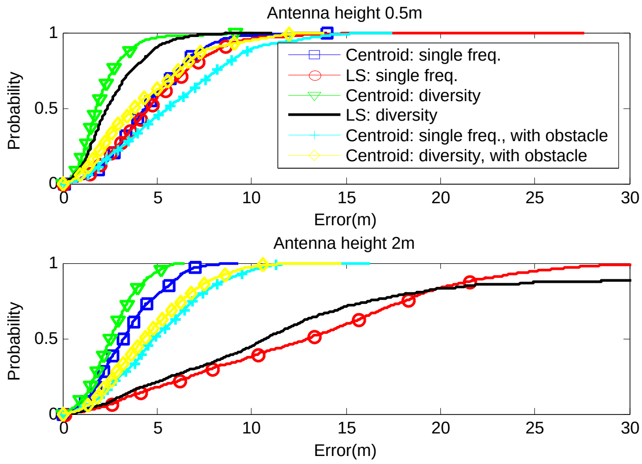

Fig. 9. Cumulative Distribution Function of the error using the least square and weighted centroid algorithms for antenna heights of 0.5m and 2 m, with single frequency and two frequencies. The effects of an obstacle for one anchor are also plotted.

V. CONCLUSIONS

In this paper we have investigated the effect of antenna height and multipath on localization problems, and have verified the range of distances where a simple slope channel model is valid for outdoor environments.

In order to study the performance of localization techniques based on RSSI measurement, two localization algorithms have been investigated: the least squared method and the weighted centroid method. It has been shown that the latter has much better performance and, in addition, it does not need any channel model. Thus no previous in-situ calibration is needed.

The use of RSSI measurement at two frequencies has also been proposed in order to mitigate the effect of multipath fading. To this end, the channel must be uncorrelated at the two frequencies, which is a function of the frequency separation and the environment (then the fading will not be present at the two frequencies). It has been shown that this condition is possible if two frequencies separated 80 MHz within the 2.4GHz ISM band are used. When the least squared method is applied, the attenuation is reduced, since an average RSSI between the two frequencies is considered. In the weighted centroid method, since the measurement with less power (for instance due to fading) has less weight, low-power measurements are practically neglected compared with stronger measurements. Frequency diversity has been shown to be useful, especially for high antennas and using the centroid method.

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