Evaluation of Range-based Methods for Localization in Grain Storages

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Abstract: Monitoring biomass storages by using wireless sensor networks with localization capabilities can help prevent economic losses during storage, help to improve the grain quality and lower costs during drying. In this article, the received signal strength was used to perform localization of wireless sensor nodes embedded in a grain storage. A path loss model that takes into account the temperature and moisture content of the grain at each sensor node was used for estimating distance based on received signal strength. The average error of the position estimates was 6.3 m. Tests using near-field electromagnetic ranging were performed to evaluate the performance of the method. It was found that the experimental setup worked best between 2 - 7 m where the average error was 4.9% of the actual distance.

1 INTRODUCTION

Many wireless sensor network (WSN) applications can benefit from nodes knowing their location. This could be for use in identification and correlation of gathered data, node addressing, geographic routing, object tracking, etc. (Boukerche et al., 2007). Biomass is biologically active or potentially active given the right conditions. When kept in a storage, this biological activity is unwanted and may result in a degradation of the quality of biomass. The combination of continuous monitoring and localization provides the information needed to limit the biomass degradation. In the case of grains and seeds (grain from here on), storage is usually preceded by a drying process to lower the moisture content of the grain to a level that ensures minimal biological activity while still providing a good quality crop for the intended use. The main expenses of the drying process are the cost of fuel and electrical power for heaters and fans (Mühlbauer, 1986). By using a WSN with localization capability, it enables the user to see the moisture content from different sections of the grain and only dry the sections that have not reached the desired moisture content. This lowers the total amount of fuel and electricity used as the system only dries the sections in need and not the entire storage throughout the whole process. This sectioning of the storage during the drying process also helps to avoid overdrying. Overdrying happens when some sections of a storage have reached the desired moisture content while other sections have not. The opposite may also happen, where the system stops before the moisture content of all the grain in the storage has been lowered to a stable level. This can result in losses during the storage period due to high biological activity.

This paper presents the experimental results of using radio signal strength (RSS) localization for positioning of wireless sensor nodes embedded in a grain storage. It also examines the potential of using a near-field electromagnetic ranging (NFER) technique in addition to RSS for localization of wireless nodes. Section 2 describes related work. Section 3 describes the theory behind the RSS localization used in this study and the theory behind NFER. Section 4 describes the experiments and results. Section 5 discusses the results of the experiments and Section 6 concludes and outlines future work.

2 LOCALIZATION METHODS

Localization in WSNs can be carried out by using various methods. However, many localization algorithms implement the same basic techniques. Those algorithms are based on finding the distance between nodes, deriving a position based on those distance measurements and lastly refine the position estimate based on the distance to other nodes (Langendoen and Reijers, 2003). To localize a node in a WSN using this technique the literature divides different approaches

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into range-based and range-free methods, see Fig. 1. Range-based techniques use distance estimates or angle estimates in location calculations while range-free techniques depend only on the contents of received messages (Hu and Evans, 2004).

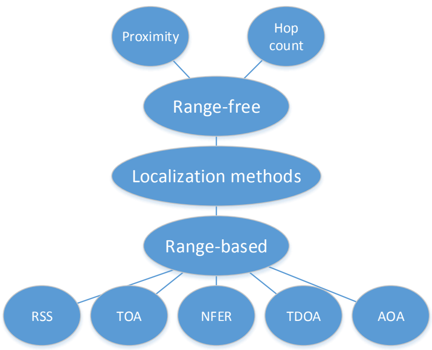


Figure 1: Overview of localization methods.

Proximity methods are among the range-free localization techniques that provide a coarse localization of a node. These methods do not measure distance directly, rather they rely on the number of node-hops required to reach a destination node (Kumar and Lobiyal, 2013) or on the connectivity by determining which fixed-position anchors are within range. As this approach requires no special equipment, the use cases are many, especially in WSNs with many nodes. It has been demonstrated that by assuming a sensor node was located on the centroid between anchors in range, it could be located with an error of less than 30% of the distance between the beacons (Bulusu et al., 2000). However, the presence of multipathing, noisy environments, dead spots, and fading, etc. is likely to reduce the accuracy of the localization.

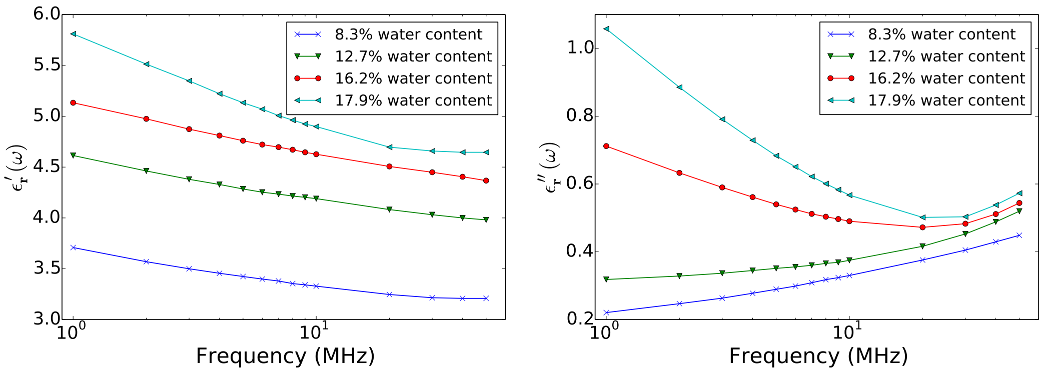
RSS has been used both as a range-free and a range-based method. An advantage of RSS-based methods is that almost any radio chip supports RSS measurements. It is possible to translate RSS to range using a path loss model. The model should be chosen with care as it is very sensitive to the environment where the node is deployed. It has been investigated how well RSS performs in real situations (Whitehouse et al., 2007). Several parameters such as attenuation coefficient and effective range of communication were characterized by using a large number of wireless nodes in different settings. Comparing the locations estimated from RSS measurements of 49 nodes to GPS data, standard error in location of 4 m was achieved.

Time-of-arrival (TOA) has also been used for localization (Gezici and Poor, 2009). A well-known example of a one-way TOA system is the Global Positioning System (GPS). The one-way TOA approach requires stringent clock synchronization between the nodes and low-jitter clocks on the nodes (Gezici and Poor, 2009). Two-way TOA is also possible. In this case, no clock synchronization is required between nodes. Instead, a delay-calibration can be performed where the delay between reception and response to a message is recorded. A study has shown that TOA localization techniques can estimate the location of a node with approximately 15 cm accuracy (Sathyan et al., 2011). Higher accuracy is possible by using a more bandwidth.

Time-difference-of-arrival (TDOA) is a variation of TOA where measurements of the time difference between the arrival of two or more signals facilitate localization. The signals can be from a single transmitter using signals with different propagation speeds, e.g. sound and radio signals, or it can be of the same type of signals transmitted from/received at multiple locations. An example of the first case is small units with ultrasonic transducers and radios as in Cricket localization-support system (Priyantha et al., 2000). The main drawbacks of such a system are the limited propagation range of the ultrasound wave and the potential interference problems with other ultrasounds sources in outdoor environments (Bulusu et al., 2000). TDOA does not require the same stringent synchronization as TOA between transmitter and receiver but clock skew and drift has to be taken into account (Xiong et al., 2015).

Angle-of-arrival (AOA) can also be used to determine location. Traditionally this is done using phase interferometry techniques and large antenna arrays. AOA has demonstrated good performance in high signal-to-noise ratio (SNR) conditions but require large antennas and fail in the presence of multipathing and co-channel interference (Rappaport et al., 1996). A different approach more suited for WSN is to use smart antennas for AOA estimation. These are smaller than conventional antenna arrays and can be used with high-resolution AOA estimation algorithms such as MUSIC or ESPRIT (AlHajri et al., 2015). Applying the AOA approach to WSNs means that the nodes and anchors with AOA capabilities require special equipment, usually in the form of special antennas (Nasipuri and Li, 2002).

NFER relies on measuring the difference in phase between the electric and magnetic components in the near field of a signal. This difference can be related to the distance to the transmitter. Shantz et al. has successfully used NFER for localization and reported average position errors of 30 cm. It was noted that the error had little correlation with range but that decreasing SNR could severely affect the phase accuracy (Schantz, 2005).



(a) (b)

Figure 2: The permittivity of 'Nebred' hard red wheat at 24°C and the indicated moisture content. The density of the wheat was 768 kg/m^3 at 13% moisture content. (a) shows the relative permittivity over a range of moisture content, and (b) shows the loss factor. Graph recreated from (Nelson, 1965).

3 RSS AND NFER LOCALIZATION THEORY

The theory for RSS localization as well as the theory behind NFER is presented in this section.

3.1 Received Signal Strength

To use RSS in localization a model that relates RSS to distance has to be found. The model used in this paper to estimate the distance between a transmitter and a receiver is the log-normal path loss model as shown in Eq. (1) (Rappaport, 2002).

$$PL(d)[dBm] = PL(d_0)[dBm] - 10 \cdot n \cdot log(\frac{d}{d_0}) + X_\sigma \quad (1)$$

Here $PL(d)$ is the average received power at distance d, $PL(d_0)$ is the average measured received power at the reference distance d_0. X_σ is a zero-mean Gaussian random variable with standard deviation σ which accounts for the effect of shadowing (Rappaport, 2002). n is the path loss exponent. In free space the exponent is equal to two. In the case where the sensor nodes are embedded in biomass the exponent is higher. As can be seen in Fig. 2 the complex relative permittivity of the grain is affected by the temperature, moisture content, and frequency of the signal. This means that all these three parameters will affect the path loss of the transmitted signal. The frequency-dependent complex relative permittivity is defined as Eq. (2).

$$\varepsilon_r(\omega) = \varepsilon_r'(\omega) + j\varepsilon_r''(\omega) \quad (2)$$

Where ω is the angular frequency, $\varepsilon_r'(\omega)$ relates to the electrical energy that can be stored in the medium. $\varepsilon_r''(\omega)$ is the imaginary part of the complex relative permittivity and relates to the dissipation of energy in a material. To account for the moisture content and temperature of the grain, n is defined as:

$$n = a + b \cdot M_{H_2O} + c \cdot T \quad (3)$$

In Eq. (3), M_{H_2O} is the moisture content wet-basis of the grain. The moisture content is found by using the modified Henderson equation (ASAE Standards, 1999). T is the temperature in degrees Celcius, a, b and c are the fitting parameters. a, b and c can be found by using linear regression given measured RSS values at known distances.

Once the distance has been estimated these are to be used for 3-dimensional position estimates by using trilateration. In this case, it is the 3-dimensional position that is of interest and the trilateration problem resolves into finding the intersections of three spheres. As this gives none, one, or two solutions, knowledge of the placement of the anchors and sensor nodes can be used to eliminate solutions in the cases where more than one is found.

3.2 Near-field Electromagnetic Ranging

The near field extends to about half a wavelength λ from an electrically small antenna (Schantz, 2005) and is governed by other phenomena than those of the far-field region. In the far-field region the phase difference between the electric and magnetic components is constant. In contrast, in the near-field region of an antenna with dimensions smaller than $1/10$ of the wavelength, also called an electrically small antenna (Miron, 2006), the phase of the two components change with distance. If each of these components are measured separately and compared to each other, this can be used as a measurement of distance. The relation between distance d and phase difference $\Delta\phi$ is given by Eq. (4).

$$d = \frac{\lambda}{2\pi} \sqrt[3]{cot\Delta\phi} \quad (4)$$

Here d is the distance from between transmitter and receiver. λ is the wavelength of the signal. $\Delta\phi$ is the difference in phase between the electric and magnetic component of the radio wave. In practice, the effect can be used out to around 0.25 λ depending on the transmitted power (Kim et al., 2006). Fig. 3 shows how the phase difference changes as a function of the distance to between transmitter and receiver in fractions of the signal wavelength. NFER has several interesting characteristics. The measurement is one-way, meaning that only the receiver needs to do the measurement, and it is not required to communicate with the transmitter. The accuracy of the measurements is not affected by the available bandwidth, making the method suitable for situations where high frequency signals are difficult to use as in the case of biomass. For the phenomenon to be of use at ranges from tens to hundreds of meters frequencies between 500 kHz (λ = 600 m) to 7 MHz (λ = 42.8 m) are appropriate. Because low frequencies tend to be more resistant to multipath effects and have better penetration depth, this is another advantage of the approach. The exact choice of frequency should be done with care. The best area of operation is between 0.08λ and 0.25λ (Kim et al., 2006).

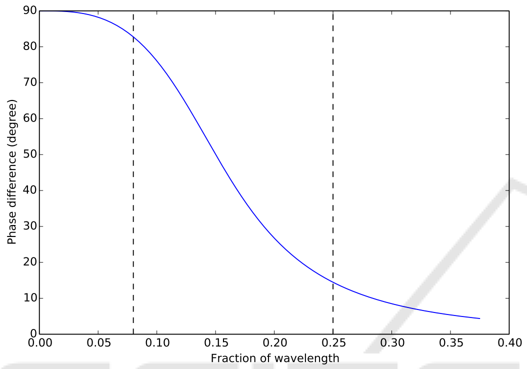


Figure 3: Plot showing the difference in phase as a result of distance from the transmitter. The interval between the vertical lines indicates the best area of operation.

4 EXPERIMENTAL SETUP AND RESULTS

To examine the use of RSS and NFER for localization in biomass two experiments were performed. The first experiment examined the performance of a system based solely on RSS measurements for localization. The second experiment examined the ranging precision of a NFER setup.

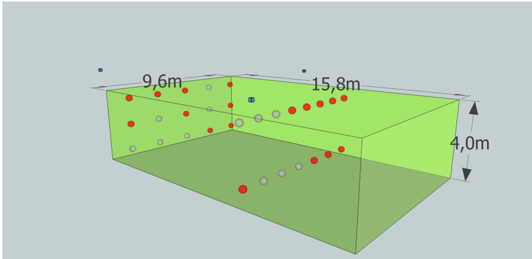


Figure 4: The placement of sensor nodes and base stations during the experiment. The spheres are sensors and the boxes are base stations.

4.1 RSS Measurements

The goal of the experiment was to find the 3-dimensional position estimates of a number of nodes deployed at known positions in a grain storage. This experiment was carried out from August 2011 to November 2011.

In the experiment 30 nodes and 3 base stations were deployed in known positions in a wheat storage as shown in Fig. 4. The dimensions of the wheat storage was 9.6m $\cdot$ 15.8m $\cdot$ 4.0m The nodes used in the experiment consist of a MSP430 microcontroller with 55 kB onboard flash and 5 kB of RAM, 1 MB external flash memory, a Semtech SX1231 radio, a 8.5 Ah lithium C-cell battery and a SHT11 temperature and relative humidity sensor. The nodes run TinyOS (Levis et al., 2005) and communicate at 433 MHz. For a more in-depth description of the system, please refer to (Juul et al., 2015).

The nodes measured and reported temperature and humidity every 5 minutes. During each transmission the RSS of the signal was recorded. The RSS measurements were averaged over 30 minute intervals and were subsequently used to try and estimate the distance from each base station to each individual sensor. This estimate was used to make a 3D-position estimate that was compared to the recorded position of the nodes. During the RSS-experiment data was received from 18 out of 30 nodes. 6 of these 18 dropped out before the end of the experiment but did deliver data for a limited period. The cause of the lack of reporting nodes was drainage of power and transmission loss. The missing nodes can be seen as gray dots in Fig. 4.

The temperature and calculated moisture content of the remaining nodes can be seen in Fig. 5 and 6. The graphs show the different conditions present in the storage and how it changes over time. The value

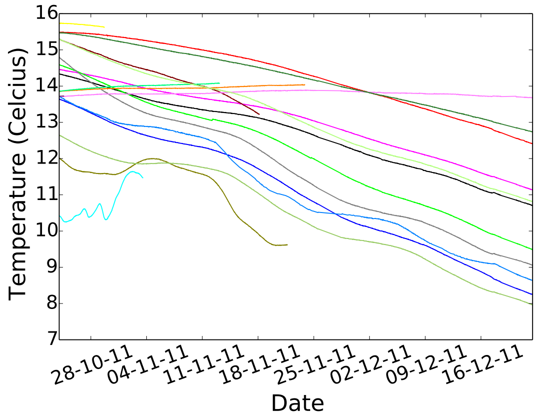


Figure 5: The temperature measured by the nodes.

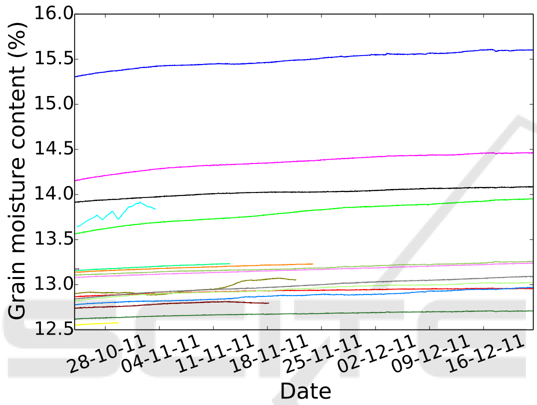


Figure 6: The moisture content wet-basis of the grain. Calculated using the modified Henderson equation (ASAE Standards, 1999).

of the fitting parameters in Eq. (3) can be found by using the measured RSS values for each node to each base station and doing least squares linear regression. The values found were a = 7.028, b = -0.082, and c = -0.016. A comparison of the actual and estimated distances can be seen in Fig. 7. The average error of the estimated distance between a base station and a node is 33.54% of the actual distance between them. The average error in meter for all measurements is 2.67 m.

Using trilateration as outlined earlier to estimate positions from the range estimates gives an average positioning error of 6.3 m.

4.2 Near-field Phase Measurements

In an effort to find a distance-based measurement to supplement RSS, work was done to study the feasibility of the NFER method. The purpose of the experiment was to measure the difference in phase between the electric and magnetic component of the radio wave at ranges of 1 to 10 m. To get the biggest change in phase at the desired range a frequency of 7.03 MHz (λ = 42.6 m) was used. Three electrically small antennas were constructed for the experiment. Two whip antennas and a box loop antenna. The whip antennas were matched to the feedline by an air core inductor and the loop by an adjustable capacitor with a range of 15 - 385 pF. A small battery powered 7.03 MHz Continuous Wave (CW) radio connected to one of the whip antennas was used as the transmitter. The receiver consisted of a N210 USRP from Ettus that had a whip and loop antenna connected to the two inputs of the device. Between antennas and the USRP was placed a ZFL-1000LN+ low-noise amplifier followed by a Bessel bandpass filter with a center frequency of 7 MHz and a passband of 500 kHz. Fig. 8 shows the experimental setup. The experiment took place on a field with line of sight between transmitter and receiver. Measurements were taken at 1 to 10 m in 1 m intervals. The transmitter was the mobile unit while the receiver was in a fixed position for all measurements. By using GNU Radio version 3.7.6, the received signal was filtered and stored in a file for offline processing. Each antenna added a constant phase shift to the measurements as they were not tuned exactly to resonance due to the limitations of the tuning circuit. The phase shift of an antenna was subtracted from the measurements made by that antenna and the

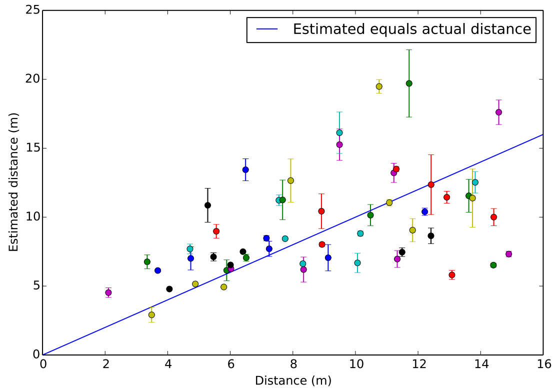


Figure 7: The estimated distance between the individual nodes and the base stations compared to the actual distance.

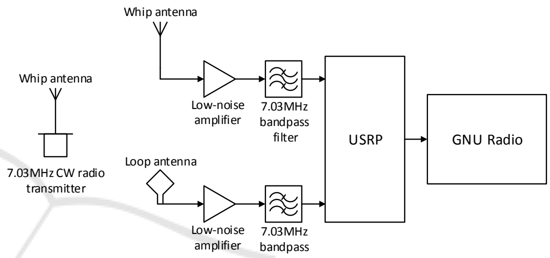


Figure 8: Diagram of the experimental setup.

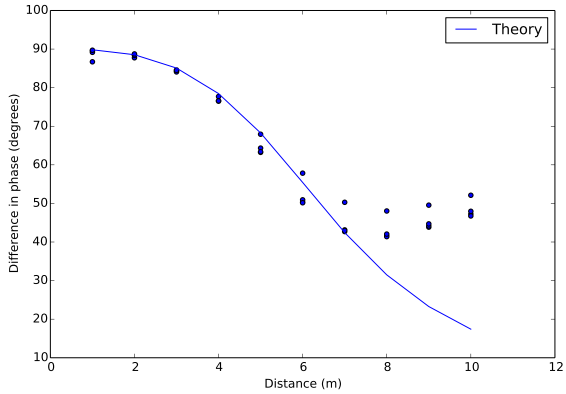


Figure 9: Theoretical and measured phase difference between magnetic and electric component of a 7.03 MHz signal in the near-field.

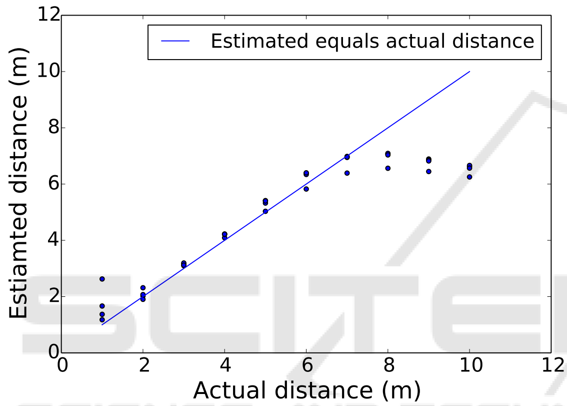


Figure 10: The range estimated from the phase difference.

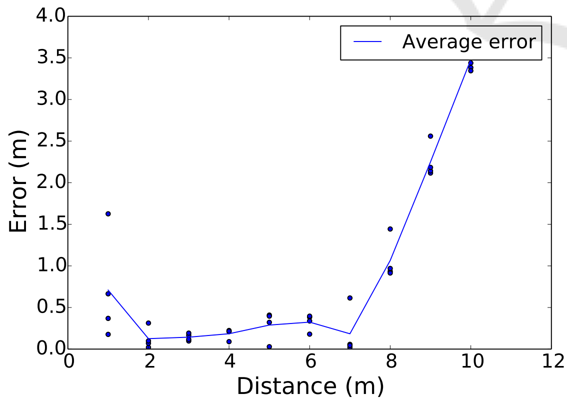


Figure 11: The estimation error at a given distance.

phase difference between the two signals was calculated. Fig. 9 shows the calculated phase difference, Fig. 10 shows the range estimates and Fig. 11 shows the estimation error at a given range.

In Fig. 9 the measured phase differences are overlaid on the theoretical phase difference at a given range. Up to approximately 7 m the curve of the theory and the curves of the measurements series fit together well. Above 7 m the measurements and theory increasingly diverge. This can also be seen in the distance estimates in Fig. 10. From 2 m to 7 m the measurements have an average error of 21 cm, and the average error at a given distance is 4.9% of the distance, see in Fig. 11. At 1 m the average error is 71 cm. This is much larger than the immediately following measurements. At this range the antenna dimensions become a significant proportion of the range and the theoretical prediction breaks down (Schantz, 2005). Looking at Fig. 11 also show that the error increases with range. This is because of the decreasing SNR as the distance between transmitter and receiver increase. The average SNR at 2 m was 57 dB and the SNR at 7 m was 28 dB.

It should be noted that the NFER measurements were done in air. When this method is applied in biomass, the increased RF absorption will lower the SNR at all ranges. The heterogeneity of the material would also contribute to measurement errors.

5 DISCUSSION

Considering the dimensions of the grain storage, a positioning error of 6.3 m for the RSS trilateration is large. Looking at the actual position estimates roughly 50% of the estimates are placed outside the storage due to estimation errors. In this experiment, only three base stations were used. Adding more bases in known positions would likely improve the estimates (Alippi and Vanini, 2006). Improving the path loss model used could also reduce error. The current model includes the temperature and moisture content at the node, but these parameters change as the signal travels through the grain, see Fig. 6. If this heterogeneity is included in the path loss model improved location estimates are expected. The same holds true if the fact that signals from different nodes travel different distances through the grain is included in the model.

At ranges from 2 to 7 m the current NFER-setup provides a range estimate with an average error of 4.9% of the actual distance and shows to be primarily limited by the SNR. This indicates that if sufficient signal is present measuring the near field phase has the potential of providing accurate and precise distance estimates. On the other hand making electrically small and efficient antennas is not trivial and is the biggest difficulty in trying to increase range and lower the error.

Table 1 compares the NFER experiment carried out here with experiments carried out with other rang-

Table 1: Comparing different ranging methods.

Name of method	Range	Accuracy	Suitability for biomass
NFER	7 m	20 cm	Partly
NFER (Schantz, 2005)	70 m	30 cm	Partly
RSS (Whitehouse et al., 2007)	50 m	4 m	Partly
TOA (Sathyan et al., 2011)	30 m	15 cm	No
TDOA, ultrasound (Balakrishnan et al., 2003)	10 m	1 cm	No
AOA (Amundson et al., 2010)	-	3°	No

ing methods. The range NFER operates in is determined by the frequency of the signal used. In the current experiment the range was limited to below 10 m while Schantz et. al. (Schantz, 2005) used a frequency of 1.295 MHz to achieve a longer range. The low frequencies used in NFER gives a higher penetration depth in materials. However, while NFER always requires an electrically small antenna, the limited space in the sensor nodes puts even shaper constraints on the size. Because of this it is only partly suitable for use in biomass.

As RSS-measurements can be made on any received signal, the approach is possible to use in biomass as long as the network can communicate. It should be noted that modeling the path loss is difficult even in good condition and the biomass makes this even more difficult to make accurate estimations. However, due to the high availability of the measurement even in this environment it is deemed partly suitable for use in biomass.

TOA require high bandwidth to provide a good accuracy (Thorbjornsen et al., 2010). The high-frequency signals needed for high bandwidth are severely attenuated by obstacles. As the nodes are to be embedded in biomass, TOA is not a suitable localization approach.

As shown in Table 1, TDOA can have a very low error. However, in the case of ultrasound TDOA, the signal has a short range in air and it would be further attenuated in biomass. Having a radio signal recorded by multiple receivers suffer from the same bandwidth limitations as TOA in biomass.

AOA is not suitable for use in biomass. The antennas needed are too large and, while beamforming has no size requirements, the heterogeneity of the biomass would change the beam pattern unpredictably, making it difficult to get accurate AOA measurements.

Based on the measurements presented here, RSS localization seems poorly suited as a stand-alone system for estimating the position of wireless sensor nodes in grain. The experiments with the NFER-approach looks promising, but as measurements have only been done in air further experiments to test the performance in grain should be carried out. Combining the two methods for localization in biomass should be investigated. The use of data fusion techniques such as weighted least squares and Kalman filters could improve position estimates compared to using only one of the methods.

6 CONCLUSIONS

This paper examines the use of RSS localization in a grain storage and NFER as a ranging method. The RSS localization had an average positioning error of 6.3 m. To minimize the error, it is suggested to use more base stations at known positions and put more effort into refining the path loss model used. Investigations were made on using NFER for localization. A first experiment tested NFER localization in air, and the feasible distance of the setup was limited to distances between 2 and 7 m. These estimates had an average error of 4.9% of the actual distance.

Future work includes improving the antenna and RF circuit design to improve the SNR and then test NFER in a grain storage. Furthermore, a system combining RSS and NFER for localization should be implemented and tested in a grain storage.

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