2011 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 21-23 September 2011, Guimarães, Portugal

Link Budget for Low Bandwidth and Coded Ultrasonic Indoor Location Systems

Enrique García*, Sverre Holm**, Juan Jesús García*, Jesús Ureña*
* University of Alcalá/Department of Electronics, Alcalá de Henares, Spain. Email: enrique.garcia@depeca.uah.es
** University of Oslo/Department of Informatics, Oslo, Norway. Email: sverre@ifi.uio.no

***Abstract*—This paper gives a comparison of a low bandwidth, long range ultrasonic indoor communication system for room-level localization and a wide bandwidth coded system. The comparison is done using the link budget and focuses on range. Robustness, reliability and a range greater than 10 meters can be accomplished by coding 8 kHz bandwidth ultrasonic signals. Pseudo-random properties of the codes permit to manage simultaneous emissions by using CDMA while processing gain permits to obtain a large range with the capability of accurate positioning.**

***Keywords*—Ultrasound; codes; CDMA**

I. INTRODUCTION

In a previous work [1] a room-level accuracy ultrasonic local positioning system was developed with robust performance over range more than 10 meters. The system is based on a set of transmitters (tags) to be worn by humans or attached to objects and a set of receivers that can be mounted in the ceiling or on the walls. The transmitters send their identity when triggered by a movement sensor or a timer. The handling of multiple users is made using a Carrier Sense Multiple Access (CSMA) protocol. This implies that each user has to listen for a clear channel before attempting to transmit. The low propagation speed of ultrasonic signals implies a real chance of signal collision. Moreover, due to the lack of a protocol for prioritizing transmissions, in crowded environments some transmitters will seldom get through and others will get through much more often. In order to avoid collisions and permit a near-equal priority, the system had to have a large repeat interval per user. This affects the maximum throughput of the system, which may easily fall to less than 0.5 locations per second per room [2]. With this low throughput, there is a chance of losing some positions if people wearing the tags move from one room to another quickly. Despite these limitations, the system is used commercially [3].

One way to cope with this problem is to use the proposed RF-US system from [2], where there is only one stationary ultrasound transmitter and multiple portable receivers attached to objects or worn by humans. Once the receivers identify the signal from the transmitter, all the IDs are transferred to the infrastructure by means of an RF-system.

Another problem that is dealt with in [1][2] is the importance of long range and robustness of the ultrasonic positioning system. This is achieved by reducing the processing bandwidth to 25 Hz, which is enough for a room-level positioning system.

Another approach to multiuser environments is to use Direct Sequence Code Division Multiple Access (DS-CDMA). There exists previous work where encoding of ultrasonic signals to improve performance has used Kasami codes [4], Golay [5], Barker codes [6] Gold [7][8], LS codes [9] or *M*-Complementary Sets of Sequences [10].

In this work we want to address the problems of multiuser environments and increased robustness by using codes. The proposed solution to address those problems is another alternative to those of [1][2]. Moreover, the performance of the coded system is analyzed by using the same methodology as [1][2].

This paper is organized as follows: in section II there is a review of previous work for range estimation; in section III the proposed system is explained; later, in section IV the effects of errors to the coded system is analyzed. In section V there is an overview of safety during exposure to ultrasound signals and there is a check that the system is within accepted safety limits.

II. BACKGROUND

A. Range estimation

One advantage of the non coded system in [1] over those commented previously is the large range. The range can be predicted from the passive sonar equation in a similar way as in [1]:

$$SL - PL - NL > DT \tag{1}$$

Where SL is the source level in dB at range $R0$, which typically is at 1 meter, PL is the propagation loss due to spherical spreading, $20\log_{10}(R/R0)$, and attenuation αR, NL is the noise level and DT is the detection threshold.

The attenuation increases with relative humidity (RH) from α=0.27 dB/m (0% RH) to a maximum of α=1.33 dB/m (55% RH) at 20ºC, 1 atmosphere pressure and a frequency of 40 kHz [11].

There exist background noise level measurements at ultrasonic frequencies [12]. These measurements give a level of 70-80 dB SPL in the range 20-60 kHz in an industrial environment at a 3 kHz measurement bandwidth.

In a similar way as [2], a level of 70 dB SPL in background noise level has been used for link simulations, so the equivalent spectral noise density is 70 dB – $10\cdot\log_{10}(3000)$ = 35.2 dB/Hz. Moreover a relative humidity of 55%, a constant temperature of 20ºC and a frequency of 40 kHz (α=1.33 dB/m) has been considered for simulations.

Nevertheless, it is important to notice that there may be a variation in the noise level up to ±30 dB. The large variation in the ultrasonic noise level is different from other communication systems especially in RF, and implies an extra effort to make a robust system. In optimal detection theory is assumed a range of threshold values from 15 dB·Hz to 20 dB·Hz [13]. As in [2] a detection threshold of DT=20 dB·Hz is assumed.

First a wideband time-delay estimator system is analyzed by using Murata MA40S4S sensors. This sensor has a central frequency of 40 kHz and is capable of a nominal output of 120 dB SPL at 0.3 m or SL=110 dB SPL at 1 meter at 40 kHz. It is assumed that the bandwidth is 20% of the center frequency, that is to say, BW=8 kHz.

In this way, for the worst case (55% RH), and working with a bandwidth of 8 kHz, the range can be found from

$$110-20\log_{10}R-1.33R-(35.2+10\cdot\log(8000))>20 \quad (2)$$

This equation is depicted in Fig. 1

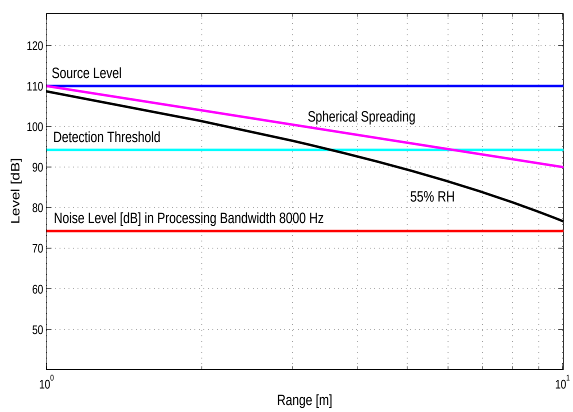

Figure 1. Received level vs. range for 40 kHz high accuracy positioning system in industrial noise. Predicted range is about 3.5 m.

The solution to equation (2) can be found when the power curve crosses the detection threshold. In this way, the minimum range is about 3.5 meters, but with the variation of the background noise level of ±30 dB the system will not work for a noise level of 100 dB, and will have a maximum range of 16 meters for a noise level of 40 dB.

So it is impossible to guarantee that the system works well under all conditions. In previous works [1][2] this problem was solved by reducing the bandwidth to 25 Hz. This removes the possibility to estimate arrival time. The system was designed for applications where only the detection of the presence of a portable receiver (tag) was needed. In such a way the noise level is reduced by 22 dB, and one obtains a range between 2.3 and 30.6 meters. In Fig. 2 is depicted the range prediction for a room-level positioning system with a processing bandwidth of 25 Hz, noise level of 70 dB SPL and a relative humidity of 55% giving a range of about 13.5 meters.

Another way to increase the range of the positioning system and robustness is to use codes; instead of reducing the processing bandwidth. This is the solution analyzed in this work.

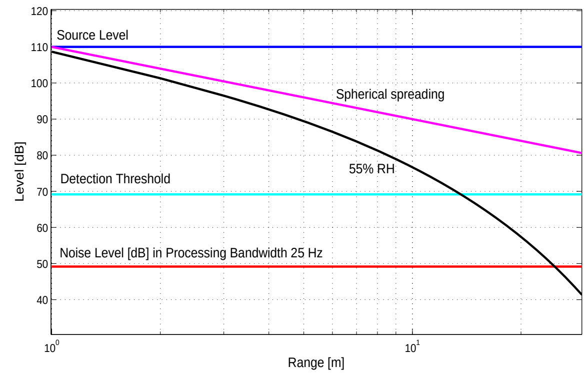

Figure 2. Received level vs. range for 40 kHz, bandwidth of 25Hz, positioning system in industrial noise. Predicted range is about 13.5 meters.

B. Coding

As was commented in the previous section, coding of ultrasonic signals has been used in several works to improve the robustness of the system.

Pseudo-random codes have very similar properties to Additive White Gaussian noise (AWGN). The codes are detected in the receiver by means of correlation techniques.

If the cross-correlation of the codes is low, then it is possible to reduce the interferences and do simultaneous emissions. Nevertheless, it is impossible to find a code with ideal properties at the same time in their autocorrelation function and in their cross-correlation function [14]. The interference caused by side lobes of the cross-correlation function is called Multiple Access Interference (MAI) while the interference caused by side lobes in the autocorrelation function is known as Inter-Symbol Interference (ISI). In order to minimize both ISI and MAI it is necessary to find codes with good correlation properties.

In the last years, the number of QS-CDMA systems (Quasi-Synchronous CDMA systems) has increased. These systems have Generalized Orthogonality (GO) properties. The sequences with GO properties, such as Loosely Synchronized (LS) codes, exhibit an Interference Free Window (IFW) in the zero displacement of the correlation functions.

For systems loosely synchronized, with a tolerance of IFW samples, it is possible to minimize ISI and MAI due to their zero correlation window in the vicinity of zero shift. Moreover, their robustness to multipath and the near-far effect compared to other codes such as Kasami or CSS [15] has been demonstrated. The only restriction is that the codes are received within the IFW. Also, in [15] one has developed an efficient correlator for LS codes, in order to permit their use in real time systems and permit to work with longer sequences.

III. Coded System

Assuring that the codes are received within a temporal window, we have chosen LS codes of length L=1151 as a candidate to code the proposed system in order to benefit from the advantages of the previous section.

By using one cycle of a square carrier as a symbol centered at 40 kHz, avoid increase the signal length and the effects of Doppler shifts. In [15] it has been checked that one cycle per symbol is enough to assure the signal fits well into the transducer bandwidth.

By applying LS codes of length 1151 to the system, one obtains a processing gain of $10 \cdot \log_{10}(1151) \cong 31$ dB.

This processing gain (PG), which comes from the effect of broadening the signal spectrum, can be added to equation (1) to determine the system range

$$SL+PG-PL-NL>DT \quad (3)$$

By using the same constraints than in the previous link budgets, the range can be obtained from

$$110+10 \cdot \log_{10}(1151) - 20\log_{10}R - 1.33R - (35.2+10 \cdot \log_{10}(8000)) > 20 \quad (4)$$

In Fig. 3 the performance of the link by using codes can be seen. In this case, for the same source level as previous links, the system has an estimated range of 16.5 meters. So there is an improvement of 13 meters compared to the link depicted in Fig. 1, where one used a bandwidth of 8 kHz too. It is important to notice that by applying codes it is necessary with a broader bandwidth than 25 Hz in order to avoid a very long emission time. Therefore, the noise level is increased by

$$10 \cdot \log_{10}(8000)-10 \cdot \log_{10}(25) = 25 \text{ dB} \quad (5)$$

It should be noted that the increase in noise level due to wider bandwidth, 25 dB, almost cancels all the processing gain due to the use of a code, 31 dB. Therefore the predicted range for this system is only slightly longer than that analyzed in Fig. 2

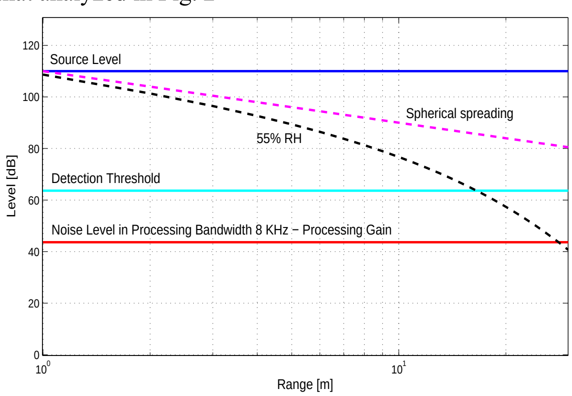

Figure 3. Received level vs. range for 40 kHz positioning system in industrial noise using codes. Predicted range is about 16.5 meters.

The processing gain can be used alternatively to reduce the source level, maintaining the same range. In this case, for the estimated range obtained in the link of Fig. 2, one needs a source level of 104 dB, lowering the source level by 6 dB.

IV. System errors

The coded system of the previous section has been analyzed in the ideal situation. In real scenarios with multiple transmitters, the near-far effect has to be considered. It occurs when the signal of an emitter reaches the receiver close to it with a large energy. As a consequence, weaker signals from emitters further away cannot be detected because their autocorrelation functions will be masked by the side lobe peaks caused by the signal received with the larger energy. In practice PN codes are not completely orthogonal. So if the emitters are not located in such a way that the power received in the coverage area is constant one will experience near-far effect. In CDMA satellite communication systems one commonly uses power control for the transmitted signals in order that the receiver shall receive a constant energy from all the emitters. This power control usually has an error with a standard deviation between 2 dB and 4 dB [16][17]. On the receiver side, there are several techniques to cope with the near-far effect, such as the use of Successive Interference Cancellation (SIC) [18]. The SIC method consists in subtracting from the received signals the emitted ones as they are being detected, improving the detection of the other emitters. In [7] this method is used to cancel near-far effects. Here it is assumed the use of power control to avoid near-far effect with an error of 4 dB [16][17].

In addition to power control errors, quasi-synchronous detection of the emitted signals by thresholding of the correlation functions can contribute errors. One can assume an error of 3 dB if the threshold is set to 50% of the ideal correlation peak. Therefore trade-offs between processing gain, noise level, the maximum range to obtain and source level needs to be done.

Fig. 4 depicts the analysis of the positioning system assuming errors of 7 dB due to power control errors and thresholding detection. As can be seen the estimated range obtained is 12.75 meters, compared to 13.5 meters for the narrowband system of Fig. 2 and 3.5 meters obtained with the non coded link of 8 kHz bandwidth of Fig. 1.

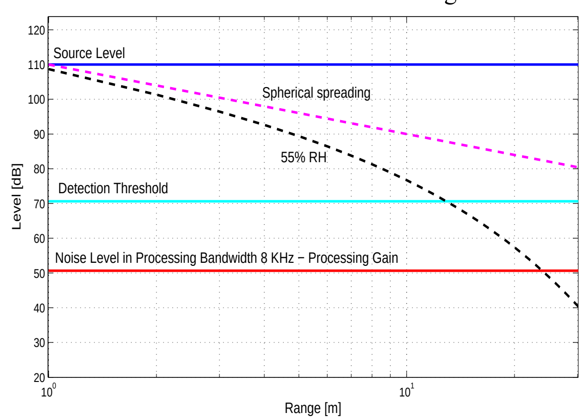

Figure 4. Received level vs. range for 40 kHz positioning system in industrial noise using codes with realistic errors assumed. Predicted range is about 12.75 meters.

Despite the fact that the range obtained is similar to that in [1][2] due to a processing gain of 31 dB which is lost by the increase of the noise level of 25 dB and the errors of 7dB, coding has several advantages; First, it can cope with crowded environments due to its better multiple access method, CDMA instead of CSMA. Moreover the number of tags can be increased without any modification to the system. Second, the system is more immune to noise and multipath giving more robustness to the link. Third the system also has the ability to find time delay with the possibility for fine positioning with an accuracy in the cm range.

V. SAFETY

Following the discussion of [2] we will now give a brief discussion of safety issues. There is no international consensus on safety of airborne ultrasound [19] and there are several guidelines for exposure limits [20][21][22]. The 1984 [20] and the Canadian 1991 [21] recommendations give 110 dB SPL as the maximum level for occupational exposure in a 1/3 octave band centered on 40 kHz. In [20], if ear protection is worn by workers, and the exposure is less than 1 hour per day, an increase up to 119 dB SPL is allowed. The guideline [21] is the most restrictive one for public exposure, lowering the limit to 100 dB SPL.

Taking into account this uncertainty in the value of ultrasound exposure limits, the proposed system is in the line of ALARA (As Low As Reasonably Achievable) principle. Taking into account that people will wear the receivers and the transmitters will be mounted in the ceiling, it is easy to ensure that the minimum distance from the ultrasonic source will be 1 meter. So the maximum human exposure to the ultrasonic source will be 110 dB. This source level is the maximum accepted by the occupational exposure limits. In real situations the exposure level is lower than 110 dB. If a distance of 3.5 meters between emitters and tags is considered, the ultrasonic level received can be lowered by $20 \cdot \log_{10}(1/3.5) = 11$ dB, due to the spherical spreading law. So the exposure level is 99 dB, which is lower than all the public limits.

VI. CONCLUSIONS

We compared two ultrasound positioning systems. The first one was a robust positioning system with a large range, which is achieved by means of reducing the processing bandwidth to 25 Hz. Multiuser access was managed with the CSMA protocol. The second system was a coded ultrasound positioning system with a wide bandwidth. This increases the noise level by 25 dB compared to the first system, but the processing gain of 31 dB compensates for the increase in the noise level, maintaining a range greater than 10 meters. Moreover it permits to manage multiuser scenarios simultaneously and endows a robust and reliable system. Also, the system has the capability of accurate positioning by time delay estimation. The appeal of the low bandwidth system is its simplicity as it does not have the high complexity and large processing requirement of the coded system. Another disadvantage of the coded system is that it requires power control in order to handle the near/far-problem. Such control can be hard to implement in practice.

REFERENCES

[1] S. Holm, "Airborne Ultrasound Data Communications: The Core of an Indoor Positioning System", in Proc. IEEE Ultrasonics Symposium, Rotterdam, Netherlands, Sep. 2005.

[2] S. Holm, "Hybrid ultrasound-RFID Indoor Positioning: Combining the Best of Both Worlds", in Proc. IEEE International Conference on RFID.

[3] L. Greenemeier, "A positioning system that goes where GPS can't," Scientific American, Jan. 2008.

[4] J. M. Villadangos; J. Ureña,; M. Mazo, et al, "Ultrasonic Local Positioning System with Large Covered Area" in Proc. IEEE International Symposium on Intelligent Signal Processing, WISP 2007, Alcalá de Henares, pages: 1-6, 2007.

[5] A. Hernández, J. Ureña, J.J. García, V. Díaz, M. Mazo, D. Hernanz, J.P. Dérutin, J. Serot, "Ultrasonic signal processing using configurable computing". 15th Triennial World Congress of the International Federation of Automatic Control (IFAC'02), Barcelona, 2002.

[6] Jesús Ureña, Manuel Mazo, J. Jesús García, Álvaro Hernández, Emilio Bueno. "Correlation Detector Based on a FPGA for Ultrasonic Sensors". Rev. Microprocessor and Microsystems. Vol. 23, no. 1, pp. 25-33. June 1999.

[7] M. Hazas and A. Ward. "A novel broadband ultrasonic location system", in Proc. Of UbiComp 2002: Ubiquitous Computing, pp: 264-280, Goteborg, Sweden, Sept. 2002.

[8] J. M. Villadangos; J. Ureña; M. Mazo, et al. "Improvement of ultrasonic beacon-based local position system using multi-access techniques" in Proc. IEEE International Workshop on Intelligent Signal Processing, 2005, Faro, pages: 352-357.

[9] Pérez, M.C; Ureña, J.; Hernandez, A. et al, "Ultrasonic beacon-based Local Positioning System using Loosely Synchronous codes", in Proc. IEEE International Symposium on Intelligent Signal Processing, WISP 2007, pages: 1-6, Alcalá de Henares, 2007.

[10] F.J. Alvarez; J. Ureña; M. Mazo et al. "High reliability outdoor sonar prototype based on efficient signal coding, 53(10), 1862-1872. DOI: 10.1109/TUFFC.2006.118, 2006.

[11] H.E. Bass; L.C. Sutherland; A.J. Zuckerwar; D.T. Blackstock; D.M.Hester; "Atmospheric absorption of sound: Further developments", Journ. Acoust. Soc. Am., vol. 97, No. 1, pp: 680-883, Jan. 1995.

[12] H. E. Bass, L. N. Bolen, "Ultrasonic background noise in industrial environments", Journ. Acoust. Soc. Am., vol 78, No. 6, pp. 2013-2016, Dec. 1985.

[13] S. Holm; "Optimum FFT-based frequency acquisition with application to COSPAS-SARSAT", IEEE Transactions on Aerospace and Electronic Systems, Vol. 29, No. 2, PP: 464-475. April 1993.

[14] L. Welch; "Lower bounds on the maximum cross correlation of signals (corresp.) IEEE Transactions on Information Theory, vol. 20, No. 3, pp: 397-299, 1974.

[15] M. C. Pérez, J. Ureña, A. Hernández, A. Jiménez, D. Ruíz, C. De Marziani, F. Álvarez, "Performance comparison of different codes in an ultrasonic positioning system using DS-CDMA" , 2009 IEEE International Symposium on Intelligent Signal Processing WISP'2009. Proceedings of the 2009 IEEE International Symposium on Intelligent Signal Processing, 978-1-4244-5058-9, pp. 125-130.

[16] A. Yu; J. Wang; "CDMA overlay in the presence of power control error", in Proc. IEE 49th Vehicular Technology Conference, vol. 3, pp: 1831-1835, 1999.

[17] Wai-Man Tam; F.C.M Lau; "Analysis of power control and its imperfections in CDMA cellular systems", in Proc. IEEE Transactions on Vehicular Technology, vol. 48, No. 5, pp: 1706-1717, 1999.

[18] A.J Viterbi; "Very low rate convolution codes for maximum theoretical performance of spread-spectrum multiple-access channels", in IEEE Journal on Selected Areas in Communications, vol. 8, No. 4, pp: 641-649. 1990.

[19] F. A. Duck, "Medical and non-medical protection standards for ultrasound and infrasound", Progress in Biophys, Molecul. Biol., Effects of ultrasound and infrasound relevant to human health, Jan.-Apr. 2007, pp 176-191.

[20] International Non-Ionizing Radiation Committee of the International Radiation Protection Association, "Interim guidelines on limits of human exposure to airborne ultrasound", Health Physiscs, Vol. 46, No. 4, pp: 969-974, April 1984 (see www.icnirp.de).

[21] Environmental Health Directorate of Canada, Guidelines for the safe use of ultrasound: part II – industrial and commercial applications. Safety Code 24, 1991.

[22] American Conference of Governmental Industrial Hygienist (ACGIH), Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposures Indices, 2003.