Subcentimeter-accuracy localization through broadband acoustic transducers

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Abstract **– Local Positioning Systems (LPS) based on acoustic transducers (mainly ultrasonic) offer accurate localization in indoor environments. However, their performance is limited by transducers' frequency band and emission pattern. This paper shows how current accuracies can be improved through the use of broadband omnidirectional transducers, methods for orientation-independent accurate ranging and bidirectional emissions. We present the 3D-LOCUS LPS system that minimizes environmental effects such as temperature and air flows, attaining localization errors below 9 mm with a 90% confidence level in an area of 4 m^2.**

Keywords **– Accurate localization, broadband transducers, local positioning systems, ubiquitous computing.**

I. Introduction

In the last few years the demand of new location-aware applications to facilitate everyday life has increased the importance of determining accurate user location. The most extended technology is the Global Positioning System (GPS), where the user carries a receiver which calculates its own position from the Times of Flight (ToF) of radio signals sent by satellites located in known positions. Typical accuracies are within few meters which can be improved up to 2 cm using differential GPS [1]. The main drawback is that such accuracies can only be achieved in outdoor environments free of any object able to impede the reception or to cause multiple paths for any signal sent by satellites. This is the reason for the development of many positioning systems with better precision, for indoor or limited environments, known as Local Positioning Systems (LPS).

The main differences among LPS alternatives arise from the technology used, influencing mainly the infrastructure needed and the accuracy achieved. Systems based on radio signals need less infrastructure than other technologies but reachable accuracy is worse: from tens of centimeters (UWB technologies based on ToF measurements [2] [3]) to several meters (based on Received Signal Strength Indicator (RSSI) used on Wifi [4], RFID [5] or mobile networks). Artificial vision developments achieve accuracies of several centimeters [6] with a very expensive infrastructure with low modularity and high processing capabilities requirements. Systems based on ultrasound signals achieve a centimeter-level accuracy being very flexible, with high modularity, and low processing demands.

In 1999 AT&T developed the Active Bat LPS [7]. The infrastructure consists of fixed beacons located on the ceiling. The user carries an ultrasonic emitter whose location is calculated in a central unit that also triggers the transmission event by a radio link. This system is capable of achieving an accuracy of 9 cm with a 95% confidence level.

In the Cricket system, beacons act as emitters of the ultrasonic signal, sending simultaneously a radio pulse for synchronization [8]. Position is calculated locally by the mobile device so that privacy is ensured. It is a very accurate system attaining errors within 2 cm.

SmartLocus makes use of the same technique as Cricket system to measure ToFs [9]. The radio signal is used besides to share location data among every node. The main novelty introduced is the capability of every node for sending or receiving the ultrasound signal, depending on whether it receives a radio pulse, asking for an emission, or it intends to calculate its own position. Another advantage is the definition of an initialization protocol for adding new nodes, which makes the system very versatile and easily expandable. Every device stores its own coordinates, being those bidimensional and referred to internal axis defined on the initialization process. Accuracy is within 20 cm.

Dolphin units, developed at Cambridge University, make use

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of hand-made transducers with wide lobe and wide frequency band [10]. Those units are either receivers or transmitters of the ultrasound signal, being arranged in two different configurations: centralized, where the mobile device is the ultrasonic emitter making the location computation in a central PC; and privacy oriented, where the mobile calculates its own position. Accuracies achieved with a 95% confidence level are 2.2 cm and 4.9 cm respectively.

From this study, several limitations of existing ultrasonic LPS can be identified: the main drawback in almost all these systems is the use of resonant transducers with several restraints: single-user access, lack of identification encoding and noise sensitivity [10]; in most of them nodes can act only as emitters or receivers; finally, none of them take into account environmental effects such as air conditioning systems or air flows.

The aim of the system presented on this paper, called 3D-LOCUS, is the development of a general location system (enabling different configurations), capable of achieving good coverage, minimizing environmental effects (as air flows and temperature changes), with high noise immunity and increased accuracy, making use of commercial transducers.

These objectives have been accomplished developing units able to work as emitters, receivers or both ways simultaneously, making use of commercial broadband omnidirectional transducers providing reliable orientation-independent inter-node ranging.

In the next section a general description of the system will be presented: firstly its architecture and functionality, secondly transducer selection, thirdly the signal design, and finally its configurability. Later, it is described the ranging calibration process which includes the search of transducers' center and ranging corrections. After that, a methodology for positioning evaluation will be presented. Next, positioning results are offered. And finally, discussion and conclusions will be made.

II. System description

A. Architecture and functionality

The 3D-LOCUS architecture is based on a homogeneous network of wired and wireless sensor nodes which are governed by a central node. A PC connected to the central node is used for high-level data processing and analysis, as well as for the global configuration of the network (fig. 1).

All units are based on Texas 150 MHz F2812 DSP hardware. Sensor nodes include emitting and receiving transducers and a driver card developed for adapting signals to and from transducers allowing the selection of the transmitting power. ToF measurements are made on the DSP through cross correlation. Communication capability enables the transmission of correlation results as well as the received signal; moreover, it permits the reconfiguration of the node. Every node is triggered simultaneously forming a synchronous network.

The central node governs the whole measurement process, configures every node and implements the interface between the network and the PC. It collects all measurements coming from nodes, sending them to the PC, and receives new configurations from the PC.

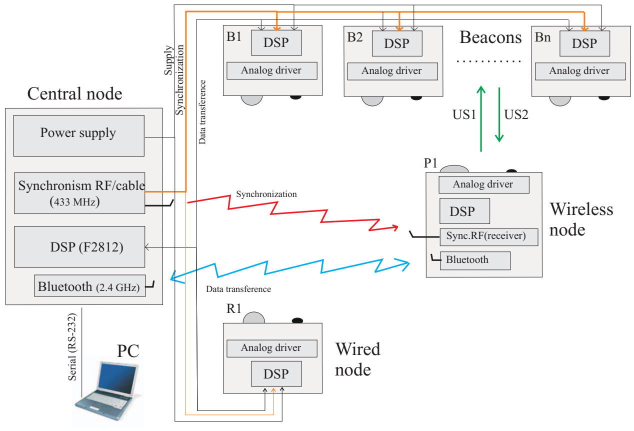


Fig. 1. 3D-LOCUS architecture

ToF measurements received at the PC are used for running the trilateration process, calculating the position of the target (in a final implementation trilateration will be accomplished by the central node or the mobile node, depending on the application). The software running on the PC enables the user to reconfigure the node network and to analyze obtained results in several ways. It is also considered the storage of sessions for off-line analysis.

Technologies implemented on every node depend on how it is connected to the central node: wired, a BusCAN network interconnects every device with the central node for data transference and a LVDS bus transfers the synchronization signal; or wireless, Bluetooth technology is used for data communication and a standard 433 MHz radio link provides synchronization.

B. Transducer selection

One of the problems presented when developing an ultrasound system is the difficulty for finding good transducers for ultrasound localization: piezoelectric transducers can act as emitters and receivers simultaneously but are narrowband, electrostatic transducers are wideband but with narrow lobe. In the last few years new materials have been introduced for the development of new transducers: PVDF [11] (with some remarkable systems developed as [10] [12]) and EMFI [13] mainly.

Due to the nonexistence of commercial ultrasonic broadband transducers with wide lobe, sonic transducers were selected. Therefore, some of the frequency band is in the audible region. The system operates in the frequency range of 5 KHz to 25 KHz.

The sonic emitter is a CP13 Visaton tweeter whose frequency response is shown in Fig. 2 (red line). The angular pattern is almost omnidirectional, being attenuated the higher frequencies as the angle approximates 90°.

The selected receiver is the WM61 Panasonic omnidirectional microphone. Its frequency response is quite flat below 45 KHz

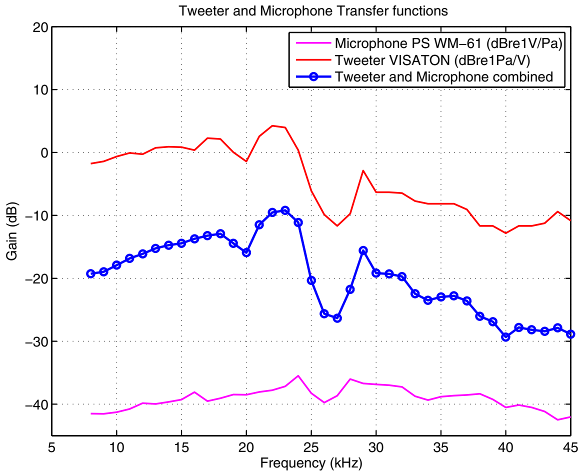


Fig. 2. MICROPHONE AND TWEETER FREQUENCY RESPONSE

as shown in fig. 2 in magenta. This transducer is completely omnidirectional due to its reduced size.

C. Signal design

In order to make use of the whole frequency band, spreading sequences are implemented. The main advantages of such sequences against tone signals are: increased noise immunity, capability of simultaneous measurements, automatic identification of the emitter and increased precision.

Golay codes (complementary pairs of two sequences) were introduced in 1961 [14]. In 1999 Popovic presented the Efficient Golay Correlator (EGC) [15] which enables the efficient computation of the cross correlation of such codes. This algorithm is much faster than those based on FFTs. Besides, it is possible to compute the cross correlation just by additions and subtractions, considering one of the signals composed by $\{1,-1\}$ symbols.

Unpaired Golay codes present similar cross correlation properties to Gold codes as long as a proper subset of sequences is selected. Consequently, there will be fewer Golay than Gold sequences with similar performance for the same code length. We use in 3D-LOCUS, because of its efficient correlation computation, preferred sets of unpaired Golay codes having the minimum cross-correlation among them. Direct sequence spread spectrum BPSK modulation is used for transmission and ranging.

D. Configurability

The node network is highly configurable from the PC. The main parameters to be selected can be divided into four groups:

- Emission configuration:
  - Code length: 32, 64 or 128 chips.
  - Code number for every node.
  - Emitting power for every node.
  - Pulses per chip: up to 8.
  - Central frequency.
- Reception configuration:
  - Start-of-acquisition delay.
  - Acquisition rate.
  - Length of acquisition buffer.
  - ToF measurement: based on the carrier or the envelope.
- Other node parameters:
  - Role: emitter or receiver.
  - Connectivity: wired or wireless.
  - Position: fixed or mobile (known or unknown).
  - Coordinates of transducers: x, y, z.
- General parameters:
  - Mode of operation: one way or bidirectional.
  - Access mode: time multiplexing (TDMA) or code multiplexing (CDMA).
  - Delay changing roles (bidirectional).
  - Radio synchronization delay.
  - Measurements update rate.

Besides, the software computes the trilateration algorithm and makes possible its configuration, e.g. sound velocity (unknown: to be estimated from redundant ranges; or known: to be estimated from a thermometer or using a reference node).

III. RANGING CALIBRATION PROCESS

The most important process setting a location system is its calibration, since every error will be magnified on every future measure. There are two main sources of systematic range errors: node orientation and system delays.

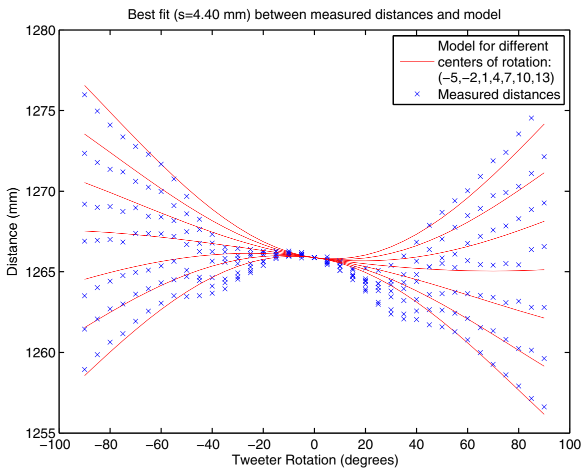
To minimize orientation dependencies, angular range variation has been measured, aiming at finding a transducer hypothetical center. Transducer's rotation around this ideal point should not affect range measurements. If the rotation is made around an axis located ahead or behind such point, the resulting distance will tend to decrease or increase, respectively, as the angle rises.

To relate ToF measurements and distance between transducers system delays will be calculated: transfer function (TF) delay (due to electronic processing and transducers) and RF synchronization delay.

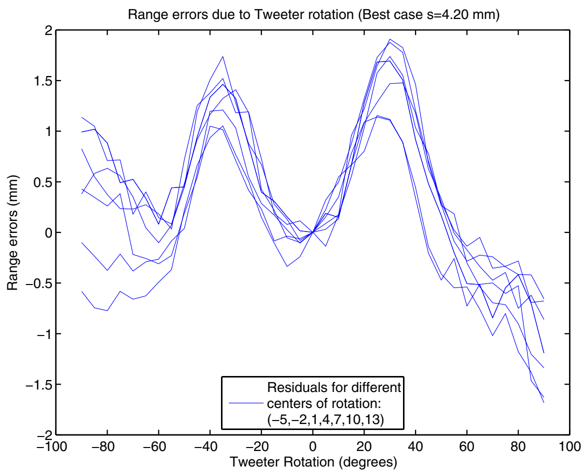
First, there will be found both transducers' centers since results obtained are necessary for delay determination, which will be presented afterwards.

A. Transducer virtual center determination

For determining hypothetical centers of both transducers, two wired nodes were brought face to face. One of them was mounted on a micrometer and a goniometer whereas the other was fixed just on a goniometer. The former's front was aligned with the rotational axis of the goniometer using a dial comparator gauge. Measurements were taken rotating the former while keeping the latter in the same position for several longitudinal displacements, changing its center of rotation. Fig. 3(a) shows resulting measurements for tweeter in blue. Every data considered is the average result of ten single measurements.



(a) Comparison between measured distances and theoretical approximation



(b) Residues for the selected center

Fig. 3. TWEETER CENTER SEARCH RESULTS FOR THE BEST ADJUSTMENT

The theoretical measurements to be obtained in the experiment were calculated for the same longitudinal displacements of the rotation axis, considering small transversal misalignments. Finally it was calculated the minimum squared error among practical and theoretical measurements considering different positions for the transducer center, s, referred to the node front. Fig. 3(a) shows the best adjustment for tweeter measured distances in red. It can be checked that the tendency is the same in theoretical and practical curves. Fig. 3(b) shows error residues for the calculated rotational center, being below 2 mm.

The same experiment was replicated for the microphone center with similar errors. Calculated centers were s=4.2 mm and s=0.4 mm for tweeter and microphone respectively.

To check these results one experiment was made in a more realistic way. The two transducer calculated centers were aligned with the axis of both goniometers, and both were rotated simultaneously in opposite directions the same angles. Results show measurement errors below three millimeters for angular displacements between -90° and 90°.

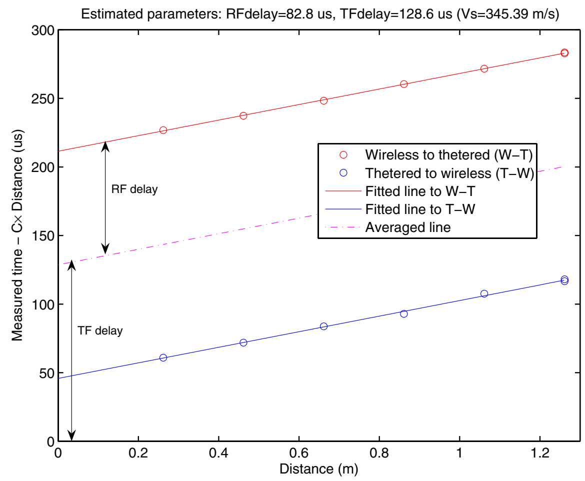


Fig. 4. LINEAR REGRESSION OF DISTANCE MEASUREMENTS TAKEN BETWEEN WIRELESS AND TETHERED NODES

B. *Ranging corrections*

In order to calculate ranging delays affecting ToF measurements nodes were fixed the same way. One of them was also fixed to a precision displacement system, able to set distances with micrometric precision for about 1 meter. Averaged ToF measurements were made at six distances. The experiment was replicated changing one of the wired nodes by a wireless one.

Both measurements were made both ways. Results were fitted to straight lines by minimizing the mean squared errors. Results for the wireless experiment are shown in fig. 4. Calculated delays correspond to the intersection of every straight line with the OY axis. Radio delay (RF) is measured as an addition or subtraction to the transfer function delay (TF) depending on whether the wireless node is the emitter or the receiver respectively.

Consequently in fig. 4 both delays are determined: 82.8 μs for RF delay and 128.6 μs for TF. The transfer function calculated delay was corroborated by means of results obtained with both tethered nodes.

IV. METHODOLOGY FOR POSITIONING ASSESSMENT

For evaluating the performance of the location network we deployed a mobile node (wireless) and eight fixed wired nodes. The evaluation area was a robotic cell (2.8 m $\times$ 2.8 m) with a Stäubli Unimation industrial robotic arm. The mobile node was affixed as its tool, oriented upwards on every position. One wired node was located inside the cell upwards and the seven remaining nodes were fixed to the cell structure downwards (fig. 5).

There were selected 32-chips-long Golay codes for transmission with one pulse per chip. Acquisition frequency was settled to 150 KHz and the length of the acquisition buffer to 2048 samples (the maximum allowed). It was defined a 3000 μs delay for the start of the acquisition process yielding a dead zone of

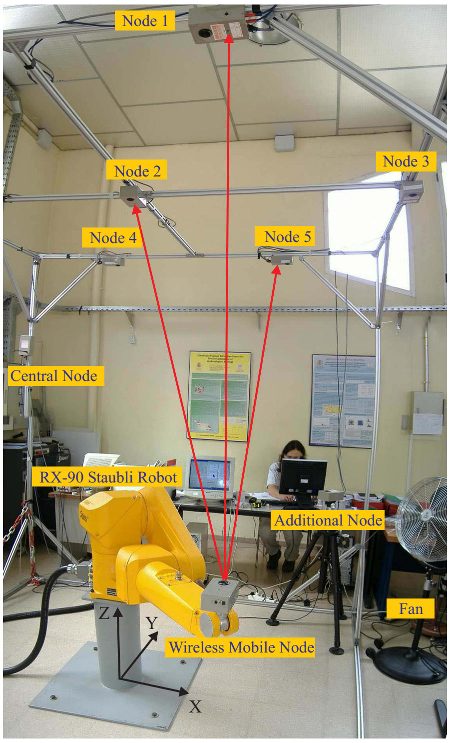


Fig. 5. ROBOTIC CELL EMPLOYED FOR SYSTEM EVALUATION

1.02 meters. The resulting measuring range was 3.92 m (from 1.02 m to 4.94 m).

Calibration of the evaluation system was performed by positioning the wireless node in four points, measuring ToFs to the emitter and the receiver of every node fixed to the cell structure. From these measurements, the sound velocity and 3D coordinates of every node's emitter and receiver were calculated.

Three different configurations were considered for evaluation:

- Centralized: the nodes oriented upwards act as emitters.
- Privacy oriented: the nodes fixed to the cell structure act as emitters.
- Bidirectional: both ways sequentially.

In the last case, both emitter and receiver positions are determined. It is considered the middle point as the resulting position.

For testing the accuracy of the system in different conditions 22 test positions were defined and 100 measures were made for every position. One of these was in the center of the cell and the remaining 21 in 7 different "xy" points at three different heights (differing ± 20 cm).

Four test conditions were evaluated for every configuration:

- Time multiplexing (TDMA) (calm air).
- Code multiplexing (CDMA) (calm air).
- TDMA with air flows (fan stream at 2 m/s).
- CDMA with air flows (fan stream at 2 m/s).

Multiple access configurations were tested with just four downward nodes, adjusting its transmission power, in order to minimize near-far effects and reduce the multiple access

TABLE I.
VALID READINGS AND 90% CONFIDENCE LEVEL ERROR FOR CONSIDERED CONFIGURATIONS UNDER TEST CONDITIONS

Configuration		TDMA	CDMA	TDMA wind	CDMA wind
Centralized	Valid readings (%)	100	96.2	90.4	96.2
	90% confidence level error (mm)	5.2	8.6	11.1	13.7
Private	Valid readings (%)	99.8	94.7	89.5	73.9
	90% confidence level error (mm)	4.1	11	11.5	13.4
Bidirectional	Valid readings (%)	99.8	90.9	84.4	71.5
	90% confidence level error (mm)	4.1	9	4.9	7.5

interference (MAI), by an empirical formula for every "xy" test position. This transmission power was not readjusted for different heights. The two upward nodes were tested emitting the same power.

V. POSITIONING RESULTS

Coordinates obtained in the calibration process were evaluated by comparing the actual distance between emitters and receivers in every node with those calculated after calibration. The measured distance was 64.11 mm, taking into account calculated centers. The mean distance obtained throw calibration results was 63.89 mm. They differ just 0.22 mm being evaluated as a fairly appropriate calibration.

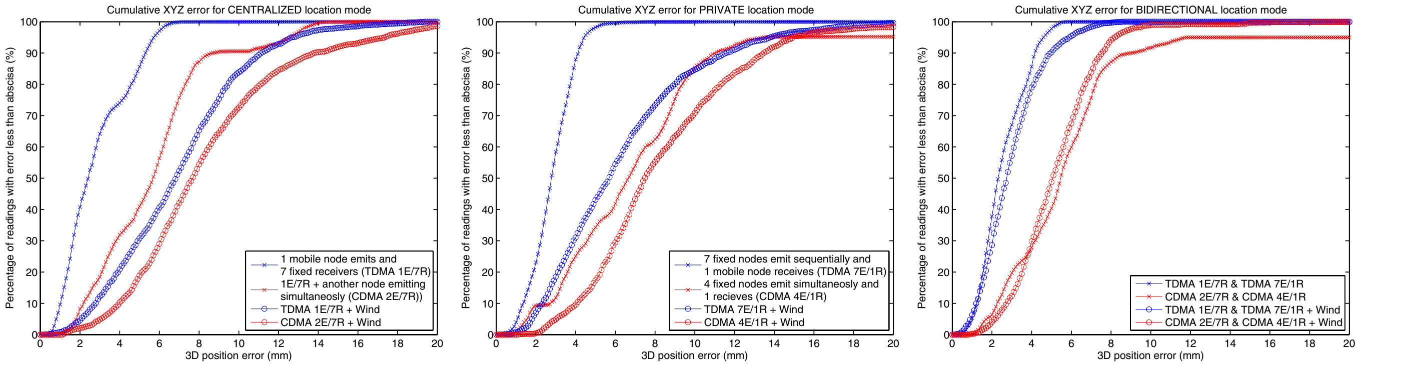
Fig. 6 shows positioning error distributions obtained under described methodology for the three considered configurations: centralized (fig. 6(a)), privacy oriented (fig. 6(b)) and bidirectional (fig. 6(c)). Table I resume the main parameters extracted from tests: valid data returned (ToF measurements are consistent) and the 90% confidence level error for these readings.

Percentage of valid readings diminished as disturbing conditions increase, changing from 100% to 71.5%. Privacy oriented configurations returned less valid data than centralized. Bidirectional measurements were a conjunction of the previous data, therefore it will always return fewer measurements than both other configurations.

Achieved accuracy varies from 4.1 mm to 13.7 mm with a 90% confidence level. It decreases as disturbing conditions increase except for bidirectional CDMA with air flows. Reached measurement errors under bidirectional configuration for wind conditions were about half times the others and for every condition were always under 1 cm for the confidence level considered. System accuracy was less influenced by wind for CDMA modes of operation than those using TDMA.

VI. DISCUSSION AND CONCLUSIONS

It has been presented an acoustic local positioning system with subcentimeter accuracy, even under air flows and multiple access, in one of its configurations. The implemented system outperforms those found on bibliography for every configuration.



(a) Centralized (b) Privacy oriented (c) Bidirectional

Fig. 6. ERROR DISTRIBUTIONS FOR CONSIDERED CONFIGURATIONS UNDER TEST CONDITIONS

Effectiveness of air flow perturbance minimization has been proved. Bidirectional mode achieves approximately similar error performance with and without air flows. This allows to consider its usability for outdoor environments.

Omnidirectionality of selected transducers permits the localization system to cover areas only restricted by maximum range measurements and geometric dilution of precision (GDOP [16]). Their characterization has shown just few millimeters ranging errors ($\pm$ 2 mm) for measurements with nodes oriented up to 90 degrees, fact that guarantees a high accurate positioning with independence of node orientations. Those small ranging errors may be attributable to multipath produced within the housing of transducers, and could be even cancelled if the orientation of the mobile node is known.

The evaluation area was restricted to the robot arm work area because of its accuracy to locate the mobile unit, necessary to evaluate system performance. The necessity to extend the evaluation area to wider spaces will require the definition of a new methodology for precisely locate mobile test points.

CDMA measurements are degraded by two highly related factors: Multiple Access Interference (MAI) and the near-far effect. The latter is due to power differences among received signals from each emitting node. It was reduced enough to enable correct measurements. This problem is under study for further improvement. MAI errors are due to the cross correlation properties of the codes (since they are not completely orthogonal) and are worsened because of the near-far effect. In this work MAI was reduced by selecting a group of codes with good cross correlation properties. Strategies to minimize its influence are under study (as Successive Interference Cancellation (SIC)).

In summary, a LPS that outperforms current systems able to precisely determine a mobile target position with the ability to compensate temperature changes, air flows and node orientation, has been developed. Future applicability for outdoor environments increases its generality for solving location requirements.

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