Indoor Positioning Based on Global Positioning System Signals

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Abstract - The Global Positioning System (GPS) is highly reliable and accurate when used outdoors. However, in indoor environments, due to the additional signal loss incurred by the walls of the buildings, the detection and decoding of GPS signals becomes a difficult task. As a solution to the indoor area coverage problem, an indoor positioning system based on GPS repeaters and a modified positioning algorithm is proposed, designed and tested. A prototype indoor positioning system for 1D/2D positioning is built using directional GPS antennas and low noise amplifiers (LNA). The modified positioning algorithm is used for the real time processing of captured live GPS data. All the system components are integrated and positioning is obtained for the evaluation of the system performance. Results of the experiments show that the proposed system can be used for indoor positioning in locations where there is no GPS signal reception. The proposed system facilitates the continuation of GPS services indoors with hardware additions to the buildings and only a software update to a standard GPS receiver.

Key words: Indoor Positioning, GPS Directional Antenna, GPS Repeater, GPS RF Low noise amplifier

1. Introduction

Civil Global Positioning System (GPS) has become very popular in recent years and it has achieved widespread use in many areas including traffic management, medical emergency services and location based services in wireless handsets and PDA's. With the latest technological advances such as Differential GPS (DGPS), Assisted GPS (AGPS), civilian GPS receivers are able to locate themselves with an error of 1-5 meters outdoors [1]. Although GPS positioning is very successful in outdoor areas, it is extremely difficult to decode the GPS signals indoors since GPS signals are attenuated by the buildings and walls. GPS signals are transmitted from satellites orbiting the earth from an altitude of 20.000 km in the sky. When these signals reach the earth surface, due to free space loss, the power level of the signals is very low (-130 dBm). For indoor areas, signals go through an additional loss of 10-30 dB [2] in which case, the signal levels become too low for a standard off-the-shelf GPS receiver. In this paper, an indoor positioning system that uses the GPS infrastructure is proposed and designed. The designed 1D/2D indoor positioning system consists of two (1D)/three (2D) GPS repeaters with directional GPS antennas and a GPS receiver with improved positioning algorithms.

In the proposed system, two/three sets of GPS repeaters with separate GPS directional antennas are used to pick up satellite signals from different parts of the sky. The received signals from the different satellites are amplified and then retransmitted into the building in which there is no GPS signal coverage. The GPS receiver with improved positioning algorithms is used to find the exact position of the receiver in a closed area. For the prototype system, a directional GPS antenna and a GPS repeater system with amplifiers are designed, manufactured and measured. Data acquisition with a GPS receiver that is capable of extracting raw GPS data is also provided. Finally, positioning algorithms are implemented on a commercially available numerical computing environment for a two GPS repeater system and, real time positioning data is obtained for the evaluation of the system performance.

The paper is organized as follows: In section II, a literature survey of indoor positioning systems is presented. Section III explains the method used for GPS based indoor positioning. In sections IV and V, hardware and software design of the indoor positioning system is explained. In section VI, measurement results for the GPS indoor system are presented.

2. Indoor Positioning Systems

A schematic view of the proposed antenna is plotted in Figure 1. The antenna has two microstrip nested patches with sizes L1, W1 designed to operate at 2.4 GHz, and L2, W2 designed to operate at 5.6 GHz. The nested patches are connected or disconnected electrically using RF pin diodes located on each side of the inner patch. RF pin diode connections will ensure the formation of x and y current densities on the inner and outer patches. To complete the return of the RF PIN diodes current, a ground return is supplied on the outer patch corners using four quarter wavelength shorted stubs which are short circuits for DC bias and open circuits at 2.4 GHz at the edges of the outer patch.

There has been a wide array of research on indoor positioning systems which utilize different kinds of physical layers such as electromagnetic waves (e.g. ultra wide band radio, RFID, wireless sensor networks), infrared, ultrasonic waves [3], vision, and optics. Although these solutions can find positions accurately in indoor areas, most of them required their own receivers and infrastructure set-up which could result in large initial deployment costs. On the other hand, there are some cost effective indoor solutions that are based on existing infrastructures such as WLAN, GSM, and Bluetooth [4-5]. As most of these systems are deployed for radio communications rather than positioning, the coverage of these solutions for positioning is limited with the infrastructure and in most cases the location calculated by using the signals of these systems may not be that accurate due to limited bandwidth and multipath propagation. Ongoing research focuses on improving the accuracy of WLAN based location systems.

Our proposed indoor positioning system uses GPS signals for positioning, therefore a standard GPS receiver with modified software can be used without any hardware additions to the receiver. The system requires an infrastructure that is only comprised of GPS repeaters and antennas, which is much simpler than that of any other positioning system that requires infrastructure installation. There are systems which repeat the GPS signal indoors using antennas and amplifiers as specified in a patent application [6]. In this application, the technique is only specified in terms of receiving the GPS signals from parts of the sky and after amplification, the signals are reradiated to indoors. This technique will suffer from the non-direct propagation of the RF signals from the satellite to the GPS receiver via the RF repeater. In our technique, algorithms are modified such that the positioning accuracy will be equal to outdoors for line of sight propagation indoors. Note that all indoor positioning systems will equally suffer from indoor multipath propagation. In [7], the application of GPS repeaters is simulated, however, non line-of-sight (NLOS) propagation through the repeaters are not taken into account and directional antennas for the reception of the satellite signals are not mentioned. In [8]-[9], sequential switching of GPS signals or time domain multiplexing is studied. In both cases, each repeater will send the GPS signal for a specified duration and then will be switched off. Because of this, the receiver should be able to track large code jumps that require large DLL bandwidths which will increase noise in the code phase measurement. Also, for the implementation of this system, significant cabling work will be required to connect all the repeaters to one single receiving antenna. In our case, all the repeaters are operated independently without the need for connections between the repeaters.

3. Overview of Indoor Positioning Based on GPS

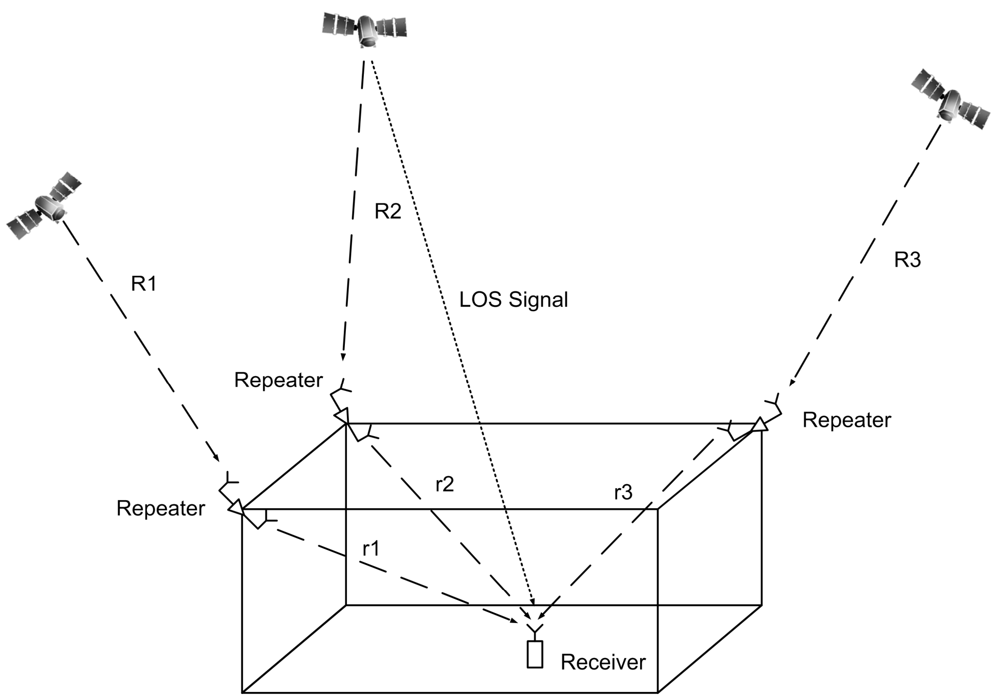

Fig. 1. Propagation of GPS signals via repeaters. Signals reaching the indoor GPS receiver trace a non line-of-sight path.

Indoor GPS reception is poor because of signal loss incurred from passing through solid walls. This loss can be compensated for by the use of repeaters. However, this solution will lead to an error in the calculated position due to non line-of-sight propagation (Fig. 1). A standard GPS receiver will solve the location equations assuming that the total distance R_i+r_i is equal to the line of sight distance which is incorrect and requires correction. The calculated distance by the GPS receiver, or the *pseudorange*, will be

$$P_i = R_i + r_i + (b + t_r)c \qquad (1)$$

where b is the clock bias, t_r is the group delay of the repeater, and c is the speed of light. P_i is called pseudorange because it involves the clock bias of the receiver as the internal clock of the receiver is not synchronized to the clocks of the satellites. Clock offset and repeater group delay will add to the distance measurements.

In the proposed system, repeaters are stationary, so the positions of the repeaters are known. The positions of the satellites can be calculated from the ephemeris which is broadcasted with the satellite radio signal. With these known positions, distance R_i can be found by using (2) where x_{sat}, y_{sat}, and z_{sat} are the coordinates of the satellite and x_{rep}, y_{rep}, and z_{rep} are the coordinates of the repeater.

$$R_i = \sqrt{(x_{sat} - x_{rep})^2 + (y_{sat} - y_{rep})^2 + (z_{sat} - z_{rep})^2} \qquad (2)$$

The satellite-to-repeater distance and the repeater group delay (which can be measured with a network analyzer) can be subtracted from the pseudorange measurement to find the *indoor pseudorange, p_i*, in terms of the repeater-receiver distance and the clock bias:

$$p_i = r_i + bc \qquad (3)$$

By using additional repeaters and calculating the distance from several repeaters with the same method, triangulation can be done and the position of the receiver can be calculated. However, one should note that in this system, clock bias is also an unknown parameter. So, in order to solve the clock bias, an additional measurement is needed as in legacy GPS algorithms. For 3D positioning, four equations and hence four pseudorange measurements are necessary (4).

$$
\begin{aligned}
&p_i = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} + bc \\
&i = 1,2,3,4
\end{aligned}
\tag{4}
$$

Here, x_i, y_i, an z_i are the coordinates of the repeaters, and x, y, and z are the coordinates of the GPS receiver. For 2D positioning, three equations will be sufficient as z will be replaced by a known altitude.

The 2D positioning example in Fig. 2 shows the difference between the conventional GPS and modified GPS algorithms. While S1, S2 and S3 represent satellite locations, R1, R2 and R3 are the repeater locations and A is the actual location of the GPS receiver. We assume that there is no clock offset for the GPS receiver at location A and that time delays through the repeaters are calibrated out, for the sake of simplicity.

If we employ conventional GPS calculations, the algorithms will search for the intersection of Lines 1, 2 and 3 and yield an erroneous position in the triangular region C even if the error free pseudorange measurements are available. The proposed algorithm, on the other hand, will compensate for the non-LOS signal, and, hence, will yield the correct position.

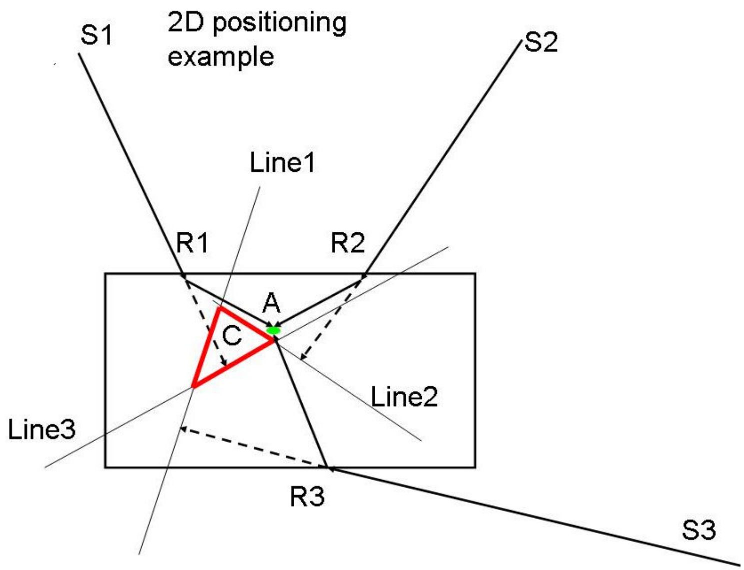

Fig. 2. Non line of sight propagation for 2D indoor GPS example. Conventional GPS algorithm will yield a position calculation at some point in triangle C. The real location of the receiver is point A.

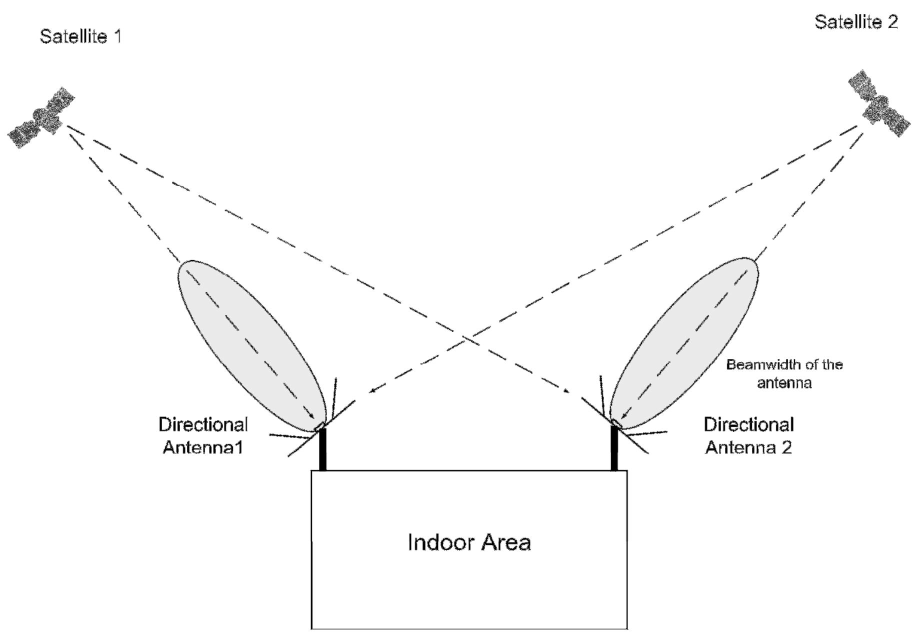

Fig. 3. Two repeaters configured for a 1D indoor GPS positioning setup. The directional antennas have non-overlapping beam patterns.

The proper functioning of the proposed system requires that individual repeaters pick signals from distinct sets of satellites. Failing to meet this requirement will not only result in signal interference, but also results in an ambiguity in the signal reception path. A simple solution for this problem is the use of directional antennas for the receiver sections of the repeaters. Directional antennas are used to pick up satellite signal from a specific area of the sky, as shown in the 1D positioning set-up of Fig. 3. One repeater may pick-up more than one satellite due to the beamwidth of the antenna; however, these satellites should not be received strongly by the other repeaters.

4. Hardware of Indoor Positioning System

Each repeater used in the GPS based indoor positioning system is composed of a directional receiver antenna, an LNA block, an additional amplifier for loss compensation, and a conventional GPS antenna to transmit the amplified signal (Fig. 4).

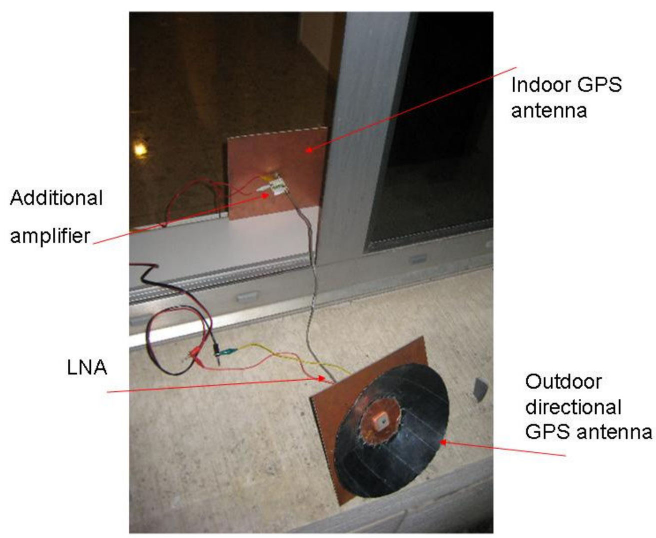

Fig. 4. Directional GPS receiving antenna linked to the indoor transmitter by a semi-rigid coaxial cable. The LNA block is at the back side of the ground plane of the receiving antenna.

A. Indoor Loss Compensation

In order to determine amplifier gains, the total loss along the signal path needs to be calculated.

The power received by the indoor GPS receiver can be found using Friis's transmission formula:

$$P_{rec} = P_{sat} G_{sat} G_{rec} \left(\frac{\lambda}{4\pi R_1}\right)^2 G_{rep,sat} G_{LNA} G_{rep,rec} \left(\frac{\lambda}{4\pi r_1}\right)^2 \quad (5)$$

where

P_{rec} : received power by the indoor GPS receiver

G_{sat} : satellite antenna gain

G_{rec} : indoor GPS receiver antenna gain

λ : wavelength (0.19 m at 1575 MHz)

R_1 : distance between satellite and the repeater

$G_{rep,sat}$: receive antenna gain of the repeater

G_{LNA} : LNA gain

$G_{rep,rec}$: transmit antenna gain of the repeater

r_1 : distance between the repeater and the receiver

The power received by the same GPS receiver when placed outdoors would have been

$$P_{rec,out} = P_{sat} G_{sat} G_{rec} \left(\frac{\lambda}{4\pi R_1}\right)^2 \quad (6)$$

From (5) and (6),

$$G_{rep,sat}G_{LNA}G_{rep,rec}(\frac{\lambda}{4\pi r_1})^2 = 1 \quad (7)$$

is the condition that should hold to have indoor signal levels that are equal to outdoor levels. Equation (7) contains a term to account for the free-space path loss (FSPL), which is a function of indoor propagation distance, r_1. Hence, when determining amplifier gains to satisfy the condition in (7), the repeater-to-receiver distance should be taken into account. For the prototype system, this distance was chosen as 4 m, for which

$$FSPL = (\frac{4\pi r_1}{\lambda})^2 = (\frac{4\pi \times 4}{0.19})^2 = 48.5dB \quad (8)$$

at 1575 MHz. (λ=0.19 m) For $G_{rep,rec}$ and $G_{rep,sat}$ values of 6 dBic and 12 dBic, respectively, a LNA with approximately 31 dB gain was required to compensate for the FSPL. GPS satellite signal levels are at -130 dBm, however most of the state-of-the-art GPS receivers are capable of locking to signals with power levels as low as -160 dBm. Consequently, the prototype system will be functional at distances up to 40 m with a GPS receiver that has 30 dB dynamic range. The GPS signals after the LNA and the transmitting antenna are amplified to their outdoor signal levels only to avoid the near-far problem.

B. Directional GPS Antenna

A standard off the shelf GPS patch antenna was used in the design of the directional antenna the directivity increase is achieved through the use of a conical reflector (Fig. 5).

Fig. 5. A standard GPS antenna and an aluminum conical reflector forming the directional GPS antenna. The measured beamwidth of the structure is 60°.

The standard GPS antenna used as a receiver is a circularly polarized microstrip patch antenna operating in the L1 band at 1575 MHz. The circular polarization is provided by truncation of the two diagonal corners and feeding the antenna asymmetrically with a coaxial probe under the patch [10]. The antenna is relatively small (25 mm × 25 mm) due to the high dielectric constant of the substrate material (ε_r = 25). The design of the conical reflector together with the patch antenna is performed using a finite element method solver for electromagnetic structures [11].

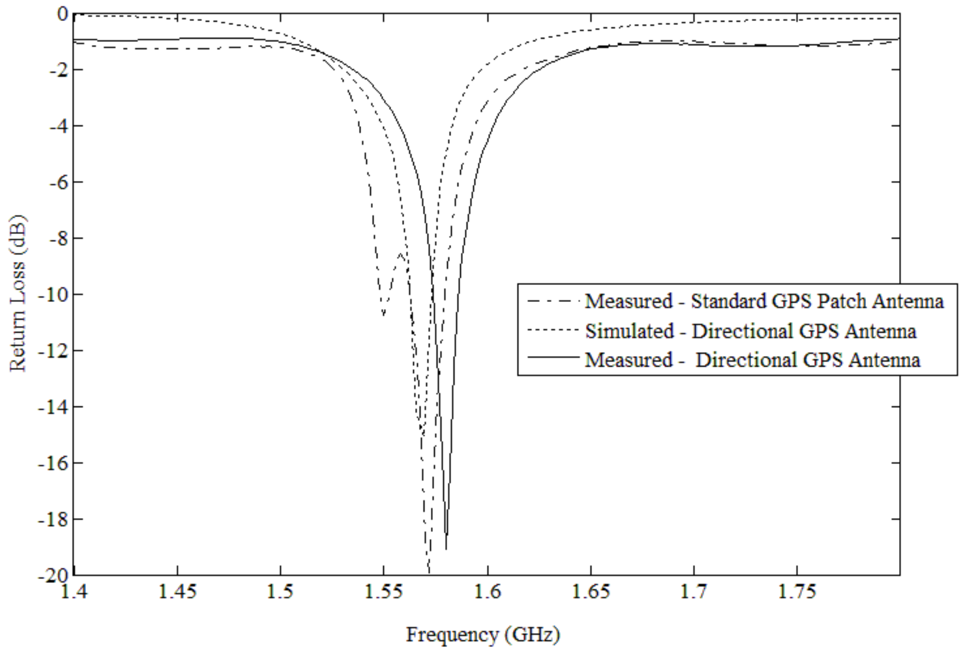

Fig. 6. Simulated and measured return loss of the GPS antenna. The conical reflector introduces a shift in the resonant frequency.

The radiation pattern of the directional antenna was measured in an anechoic chamber. Results indicate that the gain of the antenna is increased as expected. The center resonant frequency of the overall system has shifted slightly. The simulated and the measured return loss of the directional antenna along with the measured return loss of the stand alone GPS patch antenna are shown in Fig. 6. Despite the shift the resonance frequency, the directional antenna is still well matched at the GPS L1 frequency.

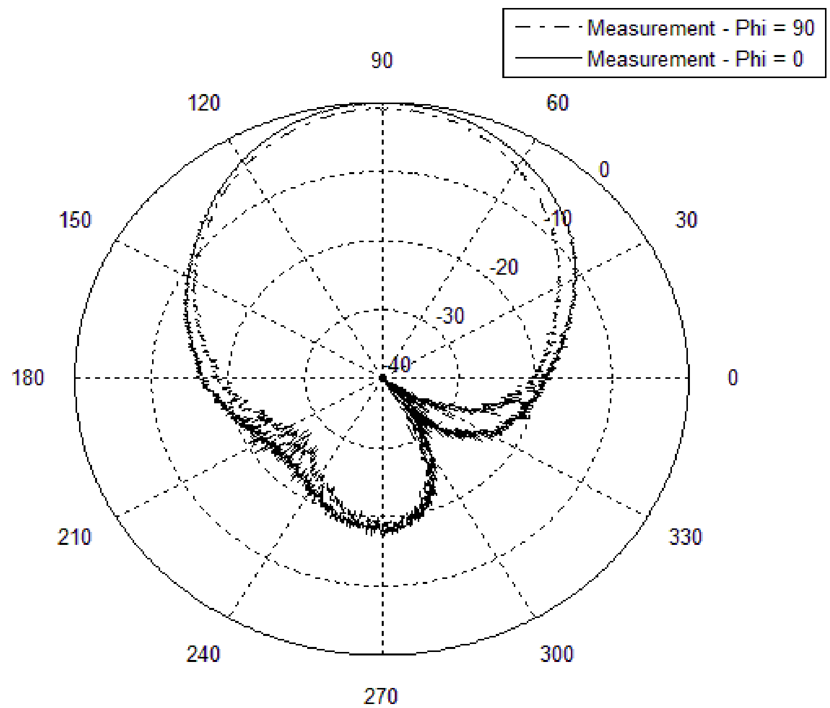

Fig. 7. Measured radiation pattern of the directional GPS antenna.

The measured radiation pattern of the directional antenna is shown in Fig. 7. The beamwidth of the directional GPS antenna is 60° in both orthogonal planes. The figure also shows that the axial ratio of the directional antenna is 1 dB which indicates that the antenna is circularly polarized. Simulated directional gain of the antenna is around 10 dBi and the measured maximum directional gain of the overall system is 9 dBi. The conical shape reflector brings an additional measured 6 dBi gain to the patch antenna. The measured results of the return loss, gain and the radiation patterns agree well with the simulation results.

C. Low Noise Amplifier

The amplifier block for FSPL compensation was designed using a selection of integrated LNAs and filters to achieve superior noise performance. Fig. 8 shows a simplified diagram of the final design.

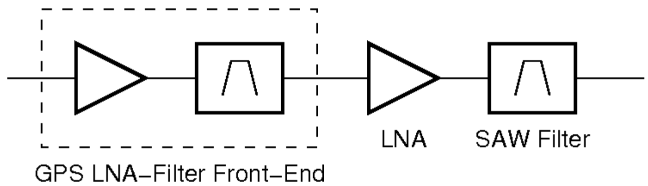

Fig. 8. RF front end LNA topology for very low noise figure. The gain of the amplifier chain is above 30 dB with a noise figure of 0.873 dB.

A GPS LNA-Filter module with superior NF characteristics constitutes the first component of the amplifier block. As the second LNA has to handle larger signal levels, an amplifier with good IP3 characteristics was chosen. The last component in the chain is a mechanical filter, which has an insertion loss of 0.53 dB, a bandwidth of 2 MHz and is internally matched to 50 Ohms at 1575 MHz. Simulated amplifier characteristics are summarized in Table I.

Table I
Simulated Amplifier Characteristics

Noise Figure	0.873 dB
Gain (S21 @ 1575 MHz)	30.3 dB
Output 1dB compression point	0 dBm
Output 3rd order interception point	8.5 dBm
S11 (50 Ω)	-13.4 dB
S22 (50 Ω)	-13.9 dB

The layout of the overall LNA circuit is printed on a FR4 board using lithography and wet etching. The manufactured amplifier is shown in Fig. 9(a). The board is enclosed in a grounded FR4 box to shield the amplifier from RF interference in general, and also from the output antenna to avoid oscillations. The manufactured amplifier board which contains discrete amplifiers, filters and bias circuitry is shown in Fig. 9(b). The noise figure and gain of the amplifier are measured as 0.91 dB and 31.5 dB, respectively, at 1.5789 GHz. The results of the network analyzer measurements are in Fig. 10. The input/output of the amplifiers are well matched and the total gain is measured as 31 dB at 1.575 GHz.

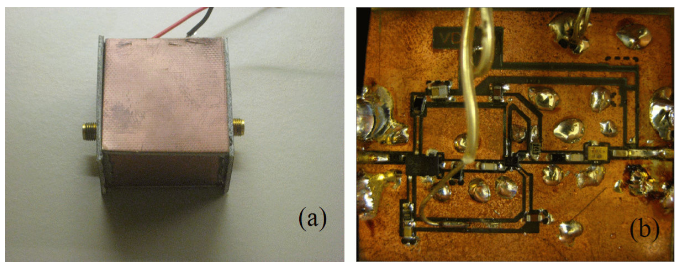

Fig. 9. RF repeater amplifier box (a), amplifier circuit board (b).

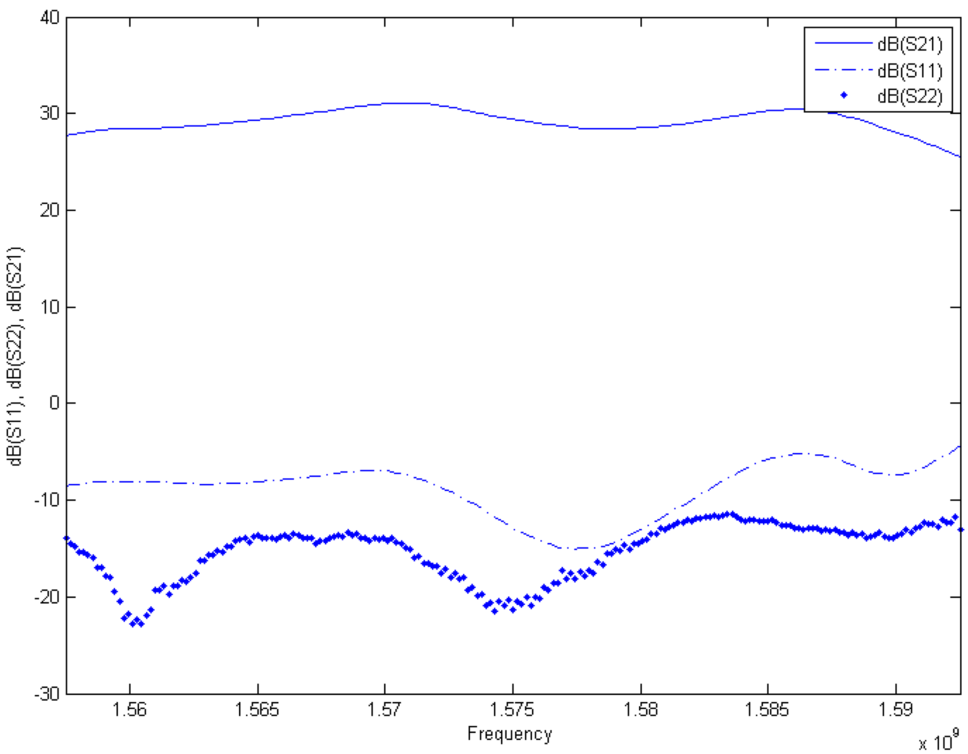

Fig. 10: Input/output reflection coefficients and gain of LNA block.

In addition to the S-parameters, group delay of the amplifier is also measured with a network analyzer and was found to be around 40 ns at 1.575 GHz. The measurement has to be performed for every individual amplifier block, and compensated for in the pesudorange calculations.

5. Software of the Indoor Positioning System

The signal reaching the indoor GPS receiver travels through a non line-of-sight path, rendering the conventional location algorithm incorrect. The proposed indoor positioning system solves this problem by performing triangulation using the repeater locations as reference points. Calculating repeater referred pseudoranges is achieved by further manipulations on the location solution of the conventional receiver.

Pseudoranges, satellite ephemeris (position of the satellite as a function of time), the ionosphere parameters, and satellite information (SV) can all be directly obtained from the GPS receiver. The clock synchronization, however, requires a number of iterations to be run on the GPS data. First, the GPS receiver is let to work out a solution for time (clock) as well as position without any change to the original GPS algorithm. This initial clock solution is very accurate for finding the satellite locations from the ephemeris message, however, is not that accurate for position of the receiver since signals arrive at the receiver by a broken path: a timing error of 1 μs will cause a distance of 300 m of error in GPS receiver position, however, it will only result in a 2.9 mm distance error in GPS satellite locations (which is the distance traversed by the satellite orbiting at 20,000 km at a speed of 2 revolutions per day). Using this timing solution, the distance between the satellite and the repeater can be calculated (as the repeater locations are known), and subtracted from the overall pseudorange measurement, yielding the receiver-to-repeater distance. This calculation has to be performed for two repeaters for 1D localization, and three repeaters for 2D localization. The modified positioning software is aware of the repeater locations as well as the direction of the receiving antennas, hence, is able to recon the path through which a particular satellite signal is received. This knowledge is essential for the correct calculation of the indoor pseudorange data.

The knowledge of satellite locations facilitates the calculation of indoor pseudorange values, which are used to perform triangulation. The location calculation is then used to correct for the clock offset by performing a few iterations on the triangulation data. During the implementation, the effects of ionosphere are removed by the Klobach model [12]. A troposphere model is not implemented because of its limited effect and due to lack of a comprehensive model. Group delays of the repeaters are measured and their effect is removed. Effects of satellite instrumentation delay and satellite clock offset are compensated. Earth rotation is taken into account and its effect is also removed.

6. Experimental Verification

The prototype system is used to perform 1D positioning in a two repeater configuration, and 2D positioning experiments were performed by the use of three repeaters. A GPS module with raw data output capability was attached to a laptop computer via the USB port, and the localization software was coded in a commercially available numerical computing environment.

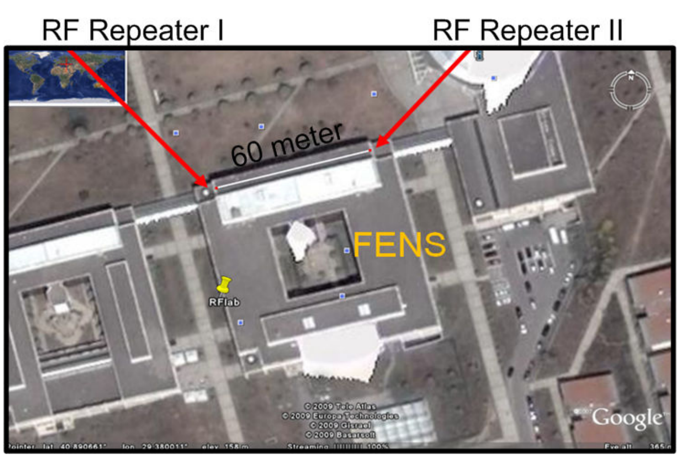

Fig. 11. Indoor positioning experiment conducted in the FENS building.

A. 1D Positioning

Measurements for 1D positioning were done in a 60 meter corridor of the Faculty of Engineering and Natural Sciences (FENS) building of Sabanci University. Repeaters were placed at the two ends of the corridor as shown on the satellite image in Fig. 11. Measurements were performed at five different locations. In every location, hundred consecutive positioning calculations were performed. Additionally, at the measurement point 12 meters away from Repeater I, a measurement was performed in a different time period, while at 18 meters the measurement was repeated by selecting different satellite pairs. In addition to the indoor measurements, a zero line test was performed by placing the GPS receiver to an outdoor location whose precise coordinates are determined from a map. A systematic bias of 2 meters was measured which results from error sources that cannot be completely removed, such as ionosphere and troposphere effects.

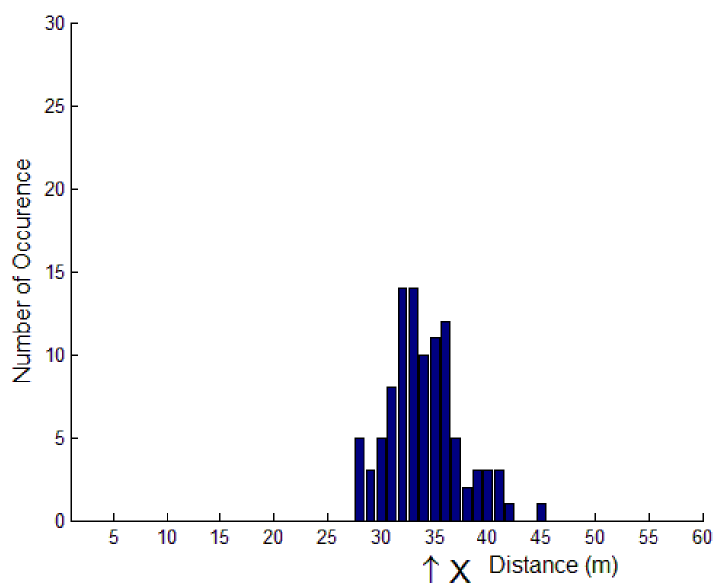

Fig. 12. A histogram of measurements made at a point 33m away from RF Repeater I. The mean is 34 m while the largest peak error is 10m. The mean error is within the systematic error made by the receiver itself.

A typical measurement result is shown in the histogram of Fig. 12. The measurement point 33 meters away from RF Repeater I. Hundred measurements were taken, and the mean distance from the repeater was found as 34 meters. The peak error made in a single measurement is 10 meters, while the systematic error of 1 meter is within the error made by the outdoor GPS receiver.

TABLE II
Summary of Measurement Results

Distance from RF repeater I (m)	**Calculated position (m)**	**Error(m)**	**Note**
12	11	1	
12	9	3	different time
18	13	5	
18	15	3	diff. sat. pair
27	31	4	
33	34	1	
50	53	3	

The measurement results for all points are summarized in Table II. Data in the table reveals that the peak error made by performing average over 100 samples is 5 m. As expected, positioning error decreases with averaging.

Experiments reveal that the proposed indoor positioning system is functional for a 1D setup, and the GPS receiver functions in an area where there is no GPS reception without the aid of the repeater hardware. It was also observed that the near/far problem was not encountered as the position of the receiver was changed from 10 to 50 meters.

B. 2D Positioning

The 2D positioning experiment has been performed in the Dining Hall of Sabanci University, which is a dome shaped structure with a diameter of 43 m. and ceiling height of 12 m. The dome is mostly metallic and all windows are metallically tinted, hence, satellite reception is poor.

Fig. 13. 2D indoor positioning experiment results imposed on the satellite image of the Dining Hall at Sabanci University. The dome shaped metallic structure of 43 m diameter blocks GPS signals.

Experiments conducted at 14:03 and 14:05 of the same day reveal that the position of the receiver can be determined by an accuracy of approximately 7 m with a systematic error of 5 m, as shown in Fig. 13. Our last experiment was at an indoor positioning demo at IPIN 2010 conference in the HXE building of ETH Zurich Hönggerberg Campus Science City. The measurement results are given in Fig. 14, in which case we could set-up the repeaters and the system in only 2 hours and obtain positioning results within ±7 m and a systematic error of 4 m.

Fig. 14. 2D indoor positioning demo at HXE building at ETH, Zurich

7. Conclusion

In this paper, an indoor positioning system is presented and its performance is evaluated through designing and manufacturing all the components and measuring the overall system. In order to analyze the overall system, directional GPS antenna is designed, manufactured and measured. A low noise amplifier is designed by the discrete components, manufactured and measured. By using antennas and the amplifier, repeater is built. In addition to these, data acquisition with a GPS is provided and novel positioning algorithms are implemented. Indoor positioning by using GPS infrastructure is a simple and low cost indoor positioning solution with promising results. It needs infrastructure addition to a building. However, the additional infrastructure is cost effective and simple. In addition to this, standard GPS receivers can be used for positioning with only a software update. Therefore, the total cost of the system is not high. Moreover, it offers continuation of a GPS service. It does not bring any additional hardware to the users. Most importantly, results of the indoor positioning system are quite comparable to outdoors GPS positioning.

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