3D Indoor Micro Location Using a Stereoscopic Microwave Phase Sensitive Device

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Abstract — **The knowledge of the spatial coordinates of an object is an inestimable information required for many applications in many fields. This information is highly needed in the telecommunication field and particularly, in the emerging context of connected objects. In this area, the environment awareness enhanced by the location based adaptability is the key of success to ensure energy efficient pervasive communication. High data rate wireless communication may also benefit from the location information by using modulation in the spatial domain, in addition to modulation in frequency, time or code domain.**

To access the spatial domain, a microwave interferometric location system (MILS), leading to a two dimensional (2D) location , has been developed. The combination of this phase sensitive device with a stereoscopic measurement allows a precise 3 dimensional (3D) indoor location. Tested, indoor and outdoor, at a frequency compatible with Bluetooth applications, this system point out the feasibility of such approach.

I. Introduction

The location and positioning concept has a long history with an incontestable apogee with the global positioning system GPS. Location and positioning are two different ways to reach the coordinates of a fixed or mobile object. With the location approach, also called remote positioning, a central operations center determines the location of the objects. This way of proceeding seems to be compatible with a centered network that needs a certain infrastructure (such as the case of radar). In the second case, also called self positioning, the objects themselves determine where they are. This second way of proceeding is suitable for a ad'hoc network that does not need any infrastructure. The GPS receiver can be included in this category. However, assuming the reciprocity of the considered models, an inherently remote positioning system can function as a self positioning system and vice versa.

Location and positioning systems involve many technologies such as dead reckoning and wave-based. For this last one, ultra sound and infrared waves are subject to failure caused by hostile environment perturbed by water, vapor, dust, smog, temperature, and the microwave solutions are not completely mature especially for indoor applications. Hence many applications requiring the determination of the spatial coordinates of an object are still addressed. Indoor and precise location are mainly highly demanded in the wireless communication area. This information is very pertinent when modulation in the spatial domain is required [1] and when optimized energy communication protocol is needed [2].

We present in this paper a 3 dimensional (3D) location solution that cross fertilizes a microwave interferometric method and a stereoscopic measurement. Assuming a free space propagation, such approach is optimal. If not, the use of several frequency modulation such as OFDM [3] or frequency hopping [4] can be used to mitigate the multipath propagation.

II. Overview Of The 2D Location Principle

The principle of the 2 dimensional (2D) location system using interferometric approach has already been presented in the literature [5].

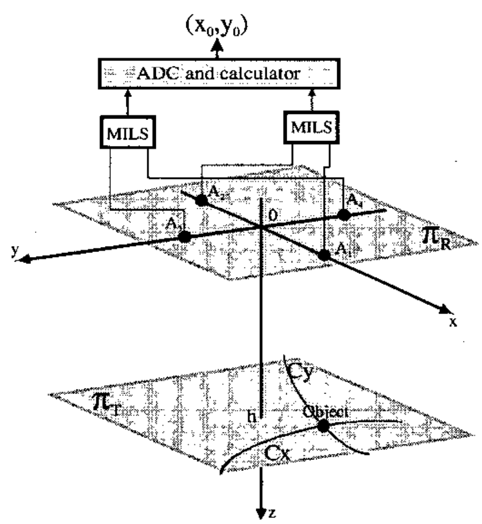

Fig.1. 2D location principle using microwave interferometry

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The fixed or mobile object, to be located in the plane π_T, fig. 1 transmits a monochromatic microwave signal (wavelength λ) towards a fixed antenna array formed by two MILS. Each MILS, fixed on the plane π_R, is formed by a pair of antennas (A_1, A_2) or (A_3, A_4) separated by a distance, called the baseline and noted 2β. Antennas outputs are connected to a phase shift measurer that gives the phase difference associated with the direct geometric path difference. The MILS associated with 0x axis measures the phase shift ϕ_x and the MILS associated with the 0y axis measures the phase shift ϕ_y. The distance between the transmitting plane π_T and the receiving plane π_R is a constant value and is noted h.

The value of the measured phase-shift ϕ_x corresponds to a certain curve (Cx) on the plane where the transmitter moves and indicates that the transmitter is located somewhere on this curve. The analytical expression of Cx can be determined from the geometry of the experimental configuration and from the transmitter frequency, and is parameterized by ϕx. Similar to the previous one, the second value of the measured phase-shift ϕ_y, defines a second curve Cy on the same plane. In principle, the intersection of the two isophase shift curves determines the location of the transmitter. The location error that results from measurement errors depends on the transmitter/receiver relative geometry and leads to the Dilution Of Precision concept (DOP) [6]. (A higher DOP corresponds to a higher position error).

In order to avoid the phase ambiguity effects, assuming a phase sensitive device, the ratio β/λ should be chosen in such a way that the phase shift variation is smaller than 360°. If this condition is not fulfilled, various techniques using phase unwrapping or widelane operation can be performed [7].

Inversion of such phase shifts, allows the determination of the coordinates (x_0,y_0) of the communicating object that can be analytically expressed by :

$$x_0 = A_x\sqrt{\frac{B_y^2(B_x^2 + A_y^2 + h^2) + A_y^2h^2}{B_x^2B_y^2 - A_x^2A_y^2}}$$

$$y_0 = A_y\sqrt{\frac{B_x^2(B_y^2 + A_x^2 + h^2) + A_x^2h^2}{B_x^2B_y^2 - A_x^2A_y^2}}$$

with (1)

$$A_x = \frac{\lambda\phi_x}{4\pi}, \quad Bx = \sqrt{\beta^2 - A_x^2}$$

$$A_y = \frac{\lambda\phi_y}{4\pi}, \quad B_y = \sqrt{\beta^2 - A_y^2}$$

This analytical approach is possible, only if the planes π_T and π_R are parallel. If not the using of the Newton-Raphson algorithm is required.

Nevertheless such solutions depend on the distance h between the transmitting and the receiving planes, which has to be known with a given accuracy. If this constraint can not be observed, a 3D location problem has to be solved.

III. 3D LOCALIZATION WITH A STERESCOPIC APPROACH

To resolve the problem related to a 3D location, a cross fertilization approach between the microwave phase sensitive location system, previously presented, and a stereoscopic arrangement is performed.

The property of a stereoscopic principle is that a 3D location problem can be seen as two different 2D location problems giving two different couples of solutions (x_1,y_1) and (x_2,y_2) depending on the third unknown coordinate z. This coordinate is reached by minimizing a cost function expressed as the Euclidean distance between those solutions.

The geometrical configuration that authorizes such approach is shown in fig. 2.

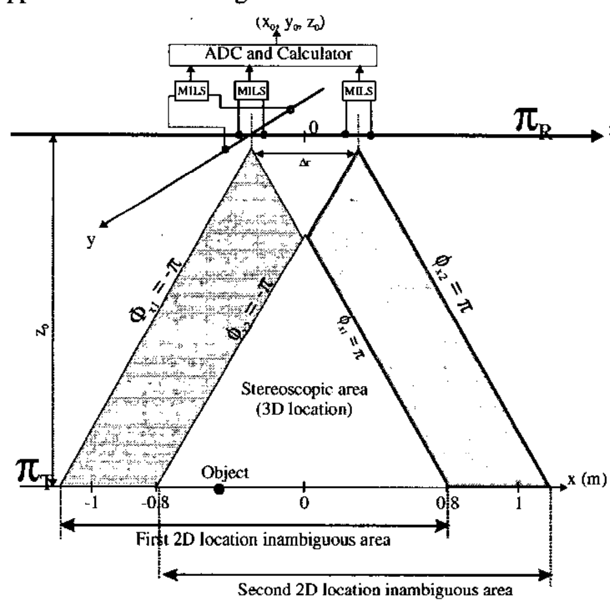

Fig.2 : 3D location principle

One MILS, located along the axe Oy, allows the measurement of the phase difference ϕ_y. The two MILS, separated by a distance Δr, depending on the wavelength λ, and fixed along the axe 0x, allow the measurement of phase shifts ϕ_{x1} and ϕ_{x2}.

The MILS giving ϕ_{x1} and ϕ_y are used to perform the first 2D location problem. The MILS giving ϕ_{x2} and ϕ_y are used to perform the second 2D location problem. The separating distance Δr contributes to decorrelate the phase shifts ϕ_{x1} and ϕ_{x2} and conditions the stereoscopic area where the 3D location is performed without any ambiguity.

With such configuration, one can obtain a first value of coordinates $(x_1(z), y_1(z))$ determined by inverting the phase shift ϕ_{x1} and ϕ_y. The second value of coordinates $(x_2(z),y_2(z))$ is obtained by inverting ϕ_{x2} and ϕ_y. The distance z assumed to be unknown, the resultant set of equation can be written

$$x_1(z) = A_{x1}\sqrt{\frac{B_y^2(B_{x1}^2 + A_y^2 + z^2) + A_y^2 z^2}{B_{x1}^2 B_y^2 - A_{x1}^2 A_y^2}}$$

$$x_2(z) = A_{x2}\sqrt{\frac{B_y^2(B_{x2}^2 + A_y^2 + z^2) + A_y^2 z^2}{B_{x2}^2 B_y^2 - A_{x2}^2 A_y^2}}$$

$$y_1(z) = A_y\sqrt{\frac{B_{x1}^2(B_y^2 + A_{x1}^2 + z^2) + A_{x1}^2 z^2}{B_{x1}^2 B_y^2 - A_{x1}^2 A_y^2}}$$

$$y_2(z) = A_y\sqrt{\frac{B_{x2}^2(B_y^2 + A_{x2}^2 + z^2) + A_{x2}^2 z^2}{B_{x2}^2 B_y^2 - A_{x2}^2 A_y^2}} \qquad (2)$$

with

$$A_{xi} = \frac{\lambda\phi_{xi}}{4\pi}, \quad B_{xi} = \sqrt{\beta^2 - A_{xi}^2}$$

$$A_y = \frac{\lambda\phi_y}{4\pi}, \quad B_y = \sqrt{\beta^2 - A_y^2}$$

To reach the actual value of z, noted z_0, a dichotomous algorithm is performed with a convergence criteria that minimizes simultaneously the distance between $|x_1 - x_2|$ and Δr and the distance between y_1 and y_2. Actual values of the transmitter coordinates can hence be written as follow :

$$x = x_0 = \frac{x_1 + x_2}{2},$$

$$y = y_0 = A_y\sqrt{\frac{B_{x1}^2\left(B_y^2 + A_{x1}^2 + z_0^2\right) + A_{x1}^2.z_0^2}{B_{x1}^2.B_y^2 - A_{x1}^2.A_y^2}} \qquad (3)$$

$$z = z_0$$

IV. Multipath Mitigation Technique

The phase shift Φ is obtained by evaluating the ratio between Q signal and I signal measured by a complex correlator [8]. Assuming a free space propagation these signals are written, for each MILS, as follow:

$$I = K\cos(\Phi), \quad Q = K\sin(\Phi) \qquad (4)$$

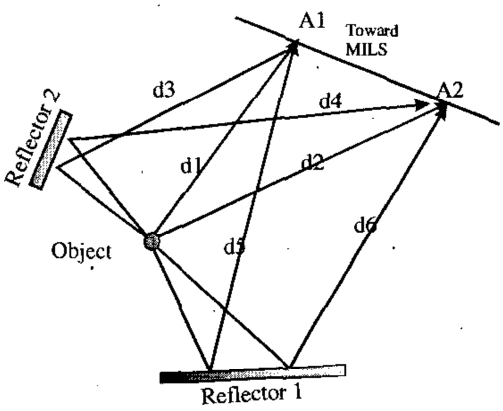

Fig. 3. Multipath channel model

With a multipath propagation channel such as modeled in fig. 3, the whole path di followed by the signals are combined into the correlator. The resultant I-Q signals are now written as follows :

$$\begin{cases} I = E_1E_2\cos(\Phi_1 - \Phi_2) + \\ \sum_{j=4}^{2k} E_1E_j\cos(\Phi_1 - \Phi_j) + \sum_{i=3}^{2k-1} E_2E_i\cos(\Phi_i - \Phi_2) + \sum_{i=3}^{2k-1}\sum_{j=4}^{2k} E_iE_j\cos(\Phi_i - \Phi_j) \\ Q = E_1E_2\sin(\Phi_1 - \Phi_2) + \\ \sum_{j=4}^{2k} E_1E_j\sin(\Phi_1 - \Phi_j) + \sum_{i=3}^{2k-1} E_2E_i\sin(\Phi_i - \Phi_2) + \sum_{i=3}^{2k-1}\sum_{j=4}^{2k} E_iE_j\sin(\Phi_i - \Phi_j) \end{cases} \qquad (5)$$

The Terms Of Interest (TOI) depict the phase difference $(\Phi_1\text{-}\Phi_2)$ related to the difference between two direct paths, and hence contains the actual location information. The parasitic terms (PT) result from the combination of two reflected signal (PTRR) i.e. $(\Phi_i\text{-}\Phi_j)$ or between one reflected signal and one direct signal (PTRD) i.e. $(\Phi_1\text{-}\Phi_j)$ or $(\Phi_i\text{-}\Phi_2)$ and hence put a strain on the error budget. Assuming a non stationary channel, PT contribute also to spread the density probability of the estimated phase shift.

Naturally the direct inversion of a such expression, by evaluation the ration Q/I, is no longer possible and a preprocessing signal is required.

The aim targeted is the mitigation of PTRR and PTRD. The PTRR is efficiently reduced by the utilization of right hand circularly polarized antennas. The reflected signals are now left hand circularly polarized and hence are affected by the cross polarization factor of the receiving antennas.

The PTRD contribution is reduced by using a multifrequency measurement. The monochromatic signal centered at F_0 is spread into a bandwidth ΔF matched to the channel coherency bandwidth. The technique of spreading may be a randomly or a sequentially frequency hopping.

The value of the phase difference is derived from the following relationship :

$$\Phi = Atan\left(\frac{\int_{\Delta F} Q(f)df}{\int_{\Delta F} I(f)df}\right) \quad (6)$$

With a such processing, the measured phase error is drastically reduced (from ±25° to ±4°). Therefore the location error is now close to several centimeters pointing out the efficiency o the multitone multipath mitigation technique.

V. EXPERIMENTAL VALIDATION

The experimental set-up is directly inspired from fig. 2 where the object to be localized is moving along the axis Ox. The coordinate y_0 is in this situation set to 0 and then the cost function is depending on x only. Each MILS is formed by two right hand circularly polarized patch antennas with a 4dBi gain and by a complex correlator. Operating at a frequency compatible with Bluetooth protocol, the baseline 2β is set to 11.6 cm and the distance Δr = 20 cm. The unknown coordinate z_0 is set to 1.65 m.

We report on table 1 the measured data compared with actual coordinates.

Table 1 : Actual and measured coordinates confrontation (F_0=2.45GHz, ΔF=100 MHz)

Actual co-ordinates (meters)			Measured co-ordinates (meters)		
x_0	y_0	z_0	$\tilde{x}$	$\tilde{y}$	$\tilde{z}$
-0.5	0	1.65	-0.51	-	1.62
0	0	1.65	0.01	-	1.64
0.5	0	1.65	0.5	-	1.66

A typical errors location of 3 cm for determining z coordinate and 1 cm for determining x coordinate are observed pointing out the ability of such approach to perform a 3D location.

VI CONCLUSION

This paper presents an original real-time method of 3D indoor location that take advantage from a cross fertilization between a microwave interferometric measurement and a stereoscopic approach. Easily handled by acting on geometrical parameters, this method, compared to classical positioning systems, requires a very limited amount of material to the achievement of small size connected devices, especially at millimeter wave. This investigation shows applications related to areas between several square meters and square decameters with an accuracy which should be compatible with a working device.

For example, besides applications to robotics, this locating system is particularly suitable for indoor application, assuming the use of multipath mitigation techniques. Hence its utilization in the emerging field of the smart objets seems to be pertinent first to enhance the context awareness for ubiquitous communication and second to save energy by adjusting power transmission between two adjacent objects.

An other advantage of such technique is its ability to allow modulation in the spatial domain for a high data rate wireless communication.

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