Millimeter wave up-converted UWB based positioning system

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Abstract

Ad hoc network connectivity and efficient energy communication require the use of optimized routing algorithms. Input data of such algorithms are the spatial coordinates of each mobile station (MS). These coordinates could be given by GPS based system or by alternative ways involving modern technology able to ensure both communication and location.
An original solution, based on a like Ultra Wide Band (UWB) technology, uses millimeter multitone dual transmission acting like a pulse composite signal and a basic millimeter receiver involving Enhanced Time Difference Of Arrival (E-TDOA) measurements.

1. Introduction

Targeting pervasive applications, the development of wireless communications encourages the emergence of smart mobile connected sensors operating at short range with high data rate and weak power consumption into a Ad Hoc network. Among the main features to ensure high quality of communication, the network connectivity, assumed by specific routing algorithms, remains the most important one. It is generally underlined, in the literature, that the optimal routing algorithm should benefit from localization and/or positioning input data to allow multi-hop network self configuration [1], [2]. This information is especially required in a network targeting energy efficient communication and encouraging solutions for the"last meter" problem [3], [4].
When operating indoor, location system matched to such applications suffer deeply from multipath contributions. Actually mainly based on direction of arrival (DOA) or multilateration process involving the time of arrival (TOA), the received signal strength (RSS) and the carrier signal phase of arrival (POA) [5], the location accuracy is dramatically decreased by the presence of multipath. Even if they are not strong, they put via the time or the phase inaccuracy, a serious strain on the location budget error.
To operate indoor GPS promoters use numerous fixed pseudolites [6] and a fixed reference station. But this approach is no longer valid for Ad Hoc networks where infrastructure is wanted as minimal as possible. Solution involving Assisted-GPS using massive parallel correlation [7] and or repeater are also proposed. A more suitable way consisting for very light infrastructure uses Ultra Wide Band technology, which is a natural approach to mitigate multipath and to allow accurate time measurement. This field is nowadays subject to many research works through the world. Using this technology, one can manage efficiently Ad Hoc networks in terms of connectivity and energy efficiency [8].
This paper describes a well matched enhanced time difference of arrival (E-TDOA) measurement for indoor applications.

2. Principle

As shown in fig 1, a fixed short pulse source (on a plane π_T), occupying a bandwidth δF, radiates through two pairs of antennas (A_1, A_2) and (A_3, A_4), a broadband signal towards numerous mobile stations (MS) moving in a given area (plane π_T).

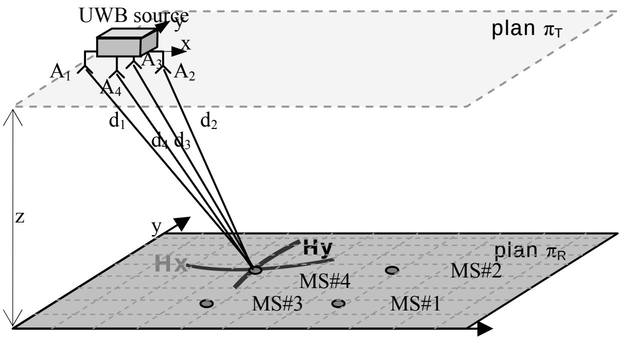

Fig. 1. : Sketch of mobile stations location

Antennas of each pair are separated by the baseline B.
At any time each MS can treat this broadcast signal to perform its two dimensional (2D) positioning, relatively to the position of the source, by means of hyperbolic inversion based on TDOA (τ_i) measurements [9].

$$\tau_1 = \frac{d_1 - d_2}{c} \qquad \tau_2 = \frac{d_3 - d_4}{c} \tag{1}$$

Three dimensional (3D) positioning is also possible assuming additional transmitting antennas [10].
For the first demonstration compatible with unlicensed UWB millimeter band, antennas A_1 and A_2 are connected to a transmitter which is designed as shown in Fig 2. A VCO, operating between 1GHz and 3GHz (ΔF=2GHz), is controlled via a DC voltage which states its central frequency f_c and via a superimposed random voltage that conditions the frequency spread δF needed to achieve a synthetic pulse. The resulting composite UWB signal is up converted to millimeter band with a local oscillator (LO). This transmitter behaves like a short pulse (δF bandwidth) that modulates many frequency carriers f_c comprised between 57GHz and 59GHz. The whole system can be considered as a double synthetic pulse source (δF and ΔF). The bandwidth ΔF is imposed by the

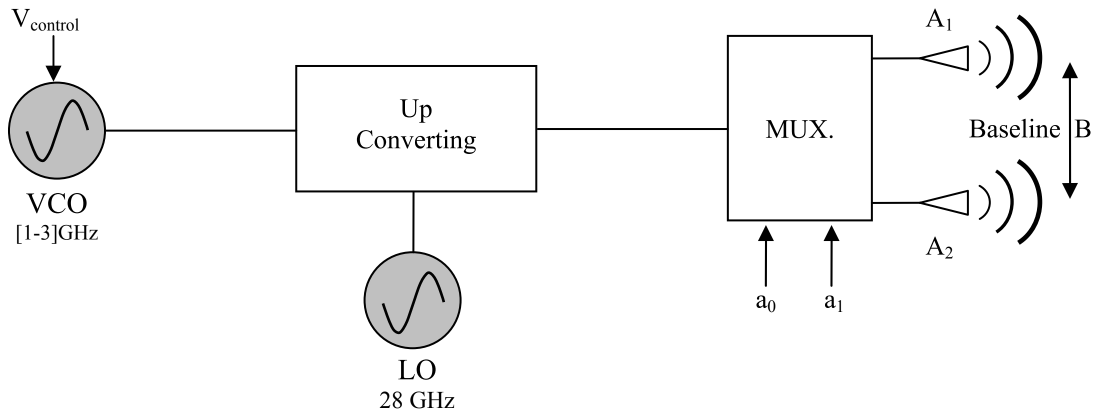

Fig. 2. : Schematic diagram of the dual transmitting principle

communication throughput and the bandwidth δF is imposed by the channel correlation bandwidth.

2.1. Source management

For clarity we consider only the pair of antennas A_1 and A_2 (Fig 2). In the first step, only antenna A_1, driven by $a_0\ \bar{a}_1$ (antenna A_2 is connected to 50Ω). In the second steps, only antenna A_2, driven by $\bar{a}_0\ a_1$ (antenna A_1 is connected to 50Ω) broadcasts, for each selected $V_{control}$, an amplitude information, towards the numerous MS moving in a the considered area Fig 1.
In the third step, the antennas A_1 and A_2 transmit sequentially, in phase signal I plus an offset driven by $a_0\ a_1$ and quadrature signal Q plus an offset driven by $\bar{a}_0\ \bar{a}_1$. At the final, each MS receives sequentially 4 signals S_i expressed as follow:

$$S_1 = E_1$$

$$S_2 = E_2$$

$$S_3 = E_1^2 + E_2^2 + 2.E_1.E_2.\cos(2.\pi.f.\tau) \qquad (2)$$

$$S_4 = E_1^2 + E_2^2 + 2.E_1.E_2.\sin(2.\pi.f.\tau)$$

Where E_i is the received signal amplitude at antenna A_i
Assuming the calculation of I-Q data expressed as follow:

$$I = K.\cos(2.\pi.f.\tau)$$

$$Q = K.\sin(2.\pi.f.\tau) \qquad (3)$$

with $K=2E_1E_2$, one can calculate the TDOA τ by evaluating the period of I or Q signals.
In the case of monochromatic source (δF=0) and assuming only Line Of Sight (LOS) propagation, I and Q signals are pure sinusoidal functions of period 1/τ (3).
To determine the TDOA τ, one can detect either the period or a part of period of I or Q versus the frequency by minimizing, using a least square criteria, a cost function formed by the difference between measured signals and templates. The templates are theoretical signals conditioned by the baseline B, the operating frequency and the unknown coordinates of the sources.
We show Fig. 3 two examples of the variation of the signal I versus the frequency. For τ =0, the signal is not frequency dependent while the signal associated with $\tau = \tau_{max} = \frac{B}{c}$, (c is the speed of the light), describes a full period considering the case of B=15cm and ΔF=2GHz

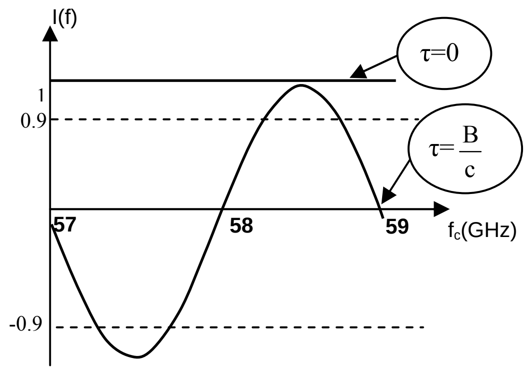

Fig. 3 : I signal versus frequency for the two extreme TDOA

Assuming the knowledge of τ_1 related to the first pair of antennas A_1 and A_2, one must also determine τ_2 related to antennas A_3 and A_4 .
Doing this, each MS can now perform its position by using a direct inversion with a well suited hyperbolic TDOA algorithm using (1)
Let us remember that this system is based on a unique fixed dual transmitter and a very simple embedded receiver. Indeed the receiver consists for a low noise amplifier and a square law detector. Time management may be carried out in the MAC layer using ARM9 microprocessor. This operating way is really suited for networks involving a very light

infrastructure and a high density of MS. In fact the number of MS is not restricted assuming each MS receives broadcast signal to perform its location. The limiting parameters is the communication capacity that depends, as shown in Fig4, on the technology which encourages the use of UWB.

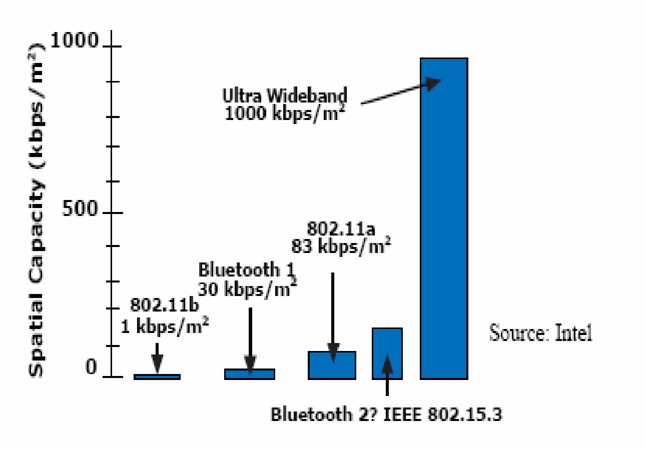

Fig. 4 Spatial capacity versus technology

2.2. Multipath consideration and δF estimation

Due to multipath propagation, direct inversion suggested previously is no longer possible because the analytical received signal S(f) = I(f) + jQ(f) differs from the simple sinusoid form and is now expressed as follow :

$$S(f) = I + jQ = \quad (4)$$

$$E_1E_2\exp(j2\pi f\tau_{LOS}) + \sum_k E_1E_k\exp(j2\pi f\tau_{NLOS1k}) +$$

$$\sum_i E_iE_2\exp(j2\pi f\tau_{NLOSi2}) + \sum_{ik} E_iE_k\exp(j2\pi f\tau_{NLOSik})$$

Where E_i is the signal amplitude linked to paths i, τ_{LOS} is the useful TDOA associated with the paths length difference (PLD) between direct paths 1 and 2, τ_{NLOS1k} is the TDOA associated with paths length difference between the LOS path 1 and the whole possible path k assuming k is an odd integer superior to 2. τ_{NLOSi2} is the TDOA associated with the paths length difference between LOS path 2 and the whole possible path i, assuming i is an even integer superior to 1. And finally τ_{NLOSik} is the TDOA associated with the paths length difference between the whole possible combinations of NLOS paths i and k assuming $i \neq 1$ and $k \neq 2$.

Due to the attenuation of propagation and to possible reflection losses, the fourth term in the previous expression, weighted by E_iE_k (with i even and superior to 1, and k odd and superior to 2), is a second order one and can be neglected. This hypothesis is particularly observed whenever circularly polarized antennas are used. Considering a ray propagation model and the celerity c, τ_{LOS} is comprised between $-\frac{B}{c}$ and $\frac{B}{c}$ and then the first term of the above generic form describes a period when the frequency spread as a bandwidth $\Delta F = \frac{c}{B}$.

In the opposite the TDOA τ_{NLOS1k} and τ_{NLOSi2} are very large in comparison with τ_{LOS} and then the second and the third term of this equation (4) vary extremely rapidly with the frequency. Hence assuming the duality between spatial domain and frequency domain, one can say that each multipath or group of multipath will produce a spectral signature that can be smoothed using UWB techniques. Otherwise a narrow random sweep δF in transmitter frequency (typically δF>500 MHz as defined for UWB communications) gives an averaged signal S(f) where the second term and the third term are mitigated. NLOS TDOA define the channel differential time coherency and contribute to determine the bandwidth. They also characterize the channel in term of coherency bandwidth [11].

The LOS contribution is separated from NLOS one by performing either an analog or digital sliding average of S(f). The resulting signal (real part I for example) is slightly the same than the signal shown in Fig. 3. Actually, due to the modulation with a "sinc" function, which argument is πδFτ, the amplitude of the sinusoid associated with the maximum TDOA is slightly less than the function associated with the null TDOA.

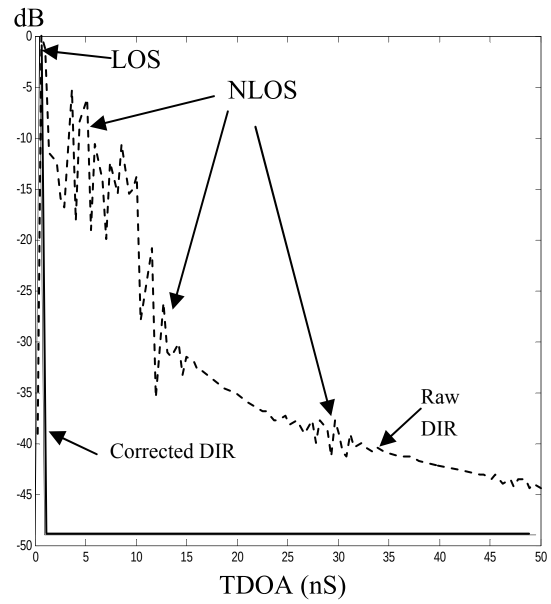

Fig. 5 : Experimental Differential Impulse Response of our laboratory [10*4]m² measured between 57GHz and 59GHz and corrected one leading to E-TDOA determination

3. E-TDOA measurements and positioning process

Targeting the location process, which has already been developed in [8], one must perform high accurate time measurement and especially Enhanced TDOA measurement.

We first determine the response of channel with a method more compatible with TDOA based applications. Usually the channel is characterized by determining the impulse response given by the inverse Fourier transform of the frequency response. We proceed in a different way more compatible with the localization algorithm because it considers a Differential Impulse Response (DIR) in the TDOA domain. For a given channel corresponding to our laboratory, a rectangular room of 10m*4m with several reflectors laid at different places, the determination of the DIR from the Fourier transform of the measured signal S(f) exhibits (Fig. 5) the both useful LOS contribution and the parasitic NLOS one.

With the dual transmitter described in Fig. 2 and assuming a very simplified microwave receiver, the corrected channel response is such as shown in Fig. 5. We show that the multipath are now drastically mitigated and we measure the only LOS TDOA contribution. Assuming this E-TDOA measurement one can now perform localization process or other TDOA based applications.

We show in fig 6, experimental results that point out that the indoor positioning accuracy is better than few centimeter, when ΔF=2GHz and δF=500MHz. With this kind of precise data, one can now perform routing algorithm to maintain connectivity and save energy.

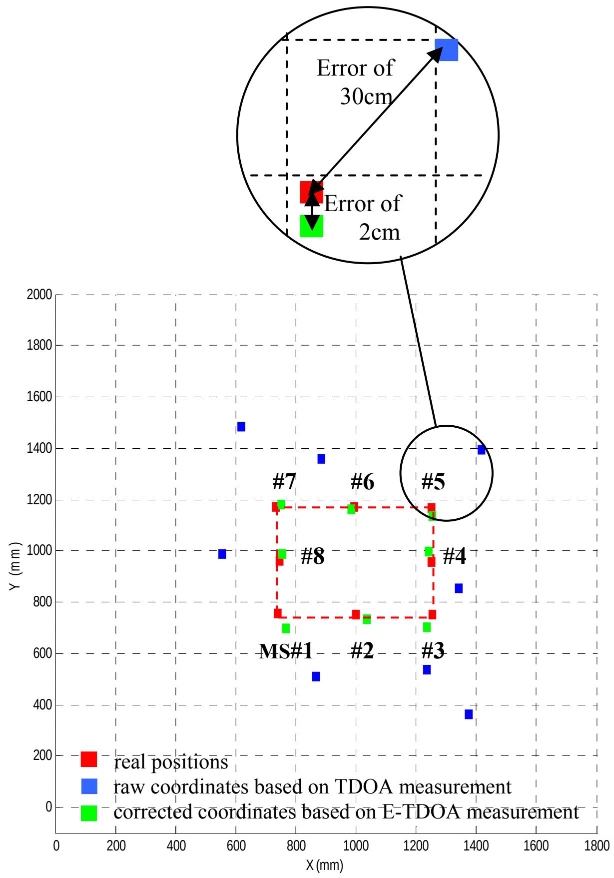

Fig. 6 : 8 mobile stations (MS) are located

4. Conclusion

Accurate location measurement involving E-TDOA is a very useful input data for routing algorithm mainly required in Ad hoc networks.

To reach this accuracy, we have developed an original way based on a the use of a like UWB communication up converted millimeter unlicensed band. This operation offers wide bandwidth for high data rate communication and offers a naturally well suited technique for accurate time measurement.

Using a particular broadcasting dual transmitter, this system allows, on one hand the mitigation of multipath propagation by using a like a pulse composite signal with 500MHz bandwidth, and on the second hand, the positioning of numerous connected mobile agents by using hyperbolic inversion of E-TDOA measured with a bandwidth of 2GHz. A third use with this approach can concern the channel sounding and associated equalization process.

By simplifying the receiver architecture, this solution meets requirement needed for embedded system and trends to be integrated with a multihop network targeting energy efficient communication and a better connectivity.

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