A RADIOLOCATION STRATEGY IN UNDERGROUND MINES USING UWB RADIO OVER AN AD-HOC STRUCTURE

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ABSTRACT

This paper gives a tutoring to radiolocation in particular indoor environments. It deals with the use of Ultra Wide Band (UWB) communications technology over a special structure, Mobile Ad-hoc Network (MANET). The suggested positioning system architecture is a c*luster-based MANET*. Its recommended physical layer, DS-UWB is beforehand discussed. An overview of the Global positioning System (GPS) signal acquisition is given to clarify easily the inspiration from that positioning system to introduce this novel radiolocation system. Also some necessary UWB's faces are explained to facilitate their efficient use in this particular application.

1. INTRODUCTION

Localization or ability to locate objects has always been essential and very important. Since first times, sailors had used their own ways to locate themselves by using celestial objects. Today GPS systems offer centimetric precision and are largely used for navigation and wireless communications [1]. Unfortunately, GPS satellites signals are not available in underground environment such as mines, where the development of a specific localization system for this environment is needed.

With the constant progress in wireless communications, it becomes essential to explore emerging new technologies to choose the optimal adoptable solution for this kind of localization application in a mining environment. Thus, it is undeniable that Ultra Wide-Band technology (UWB), recently standardized (IEEE802.15.3a) [2], seems to be a promising technology. The IEEE802.15.3a is an IEEE standard task group, also called TG3a, working on the physical layer for high bit rate Wireless Personal Area Network (WPAN). This standard is targeting data transmission at a minimum rate of 110 Mb/s over 10 meters at most [3]. The Federal Communications Commission (FCC) defined, for this new communication technology, a "new bandwidth" from 3.1 GHz to 10.6 GHz at the low power floor of -41.3 dBm/MHz, where UWB radios overlaying coexistent RF systems can operate using low-power ultra-short information bearing pulses [4]. However, in such a mining confined environment, the power limit allowed by the FCC regulations is no longer compulsory and can be exceeded. Therefore, at higher power levels, UWB signals can travel to significantly greater ranges to be very suitable for this kind of applications. To encourage institutions and companies to explore UWB technology in all its vast possible applications, the FCC has unlicensed it under its regulations, thus accelerating research and development in such a hot topic. Therefore, UWB-based localization can be very appropriate for an indoor mine application. However in spite of its substantial advantages, UWB technology adoption for any application requires detailed analyses of its adaptation problems. Considering the huge bandwidth used and the application environment nature, it is natural that respectively the problems of synchronization and multi-path will submerge in addition to possible problems related to power increasing needed. Indeed, UWB's attractive use implies a multitude of exciting new research challenges: i) propagation related measures, ii) channel modeling, iii) choosing the appropriate techniques for modulation and coding, iv) acquisition and tracking, v) fading SNR, vi) VLSI receiver implementation, vii) unavoidable RF design, viii) networking problems due to the use of smart antennas (nodes) in an Ad-hoc architecture.

Thus, in this paper a general overview is given about the most significant and obvious points to illustrate relative challenges for this positioning application.

2. POSITIONING SYSTEMS PRINCIPLES

The world knows actually three global positioning satellite-based systems. They are all characterized by the same principle.

- The Russian military positioning system, GLONASS, isn't completely operational since December 1995 due to its SVs low lifespan.
- The European GALILEO system is still under development and its deployment is envisaged for the year 2008.
- GPS system, the most widespread positioning system, was developed in 1970 by the DoD of the USA. It is based on a constellation of 24 satellites at least. Each, are identified by their CDMA coded signals which can be processed in a GPS receiver to compute position, velocity and time. Four GPS satellite signals are used to compute positions in three dimensions and the time offset in the receiver clock [1].

2.1. GPS signal

The GPS satellites signals are coded by the well-known DSSS spreading technique. The gold-code is used for its noise-like auto-correlation and cross correlation characteristics. All GPS

SVs use two frequencies for navigation purposes, known as L1 and L2. The transmission uses the OWR (One-Way-Ranging) principle. L1, with a carrier frequency of 1575.42 MHz, is used for both civilian (standard) and military (precise) positioning services, SPS and PPS respectively. Whereas L2, which uses 1227.6 MHz signal, is primarily used for military service [5]. Civilians have access to the L1 carrier C/A coded, but not to the encrypted P(Y)-code which is BPSK modulated in both L1 and L2 carriers. The civilian C/A code, called the coarse acquisition code, has a rate of 1.023 MChips/s with a code period of 1ms. The binary navigation data has a rate of 50bits/s and is bi-phase shift keyed onto the carrier signal and the C/A code is also bi-phase shift keyed onto the resulting signal. A simplified model for the transmitted SPS signal can be written as:

$$s_i(t) = A_i\, G_i(t)\, D(t)\, \sin(2\pi f_{L1} t + \phi_0) \quad (1)$$

Where A_i, is the signal amplitude, $G_i(t)$ is the C/A code for satellite number i, $D(t)$ is the navigational data, f_{L1} is the L1 carrier frequency and ϕ_0 is the carrier frequency deviation.
The SVs transmit their signals by one-way-ranging principle (OWR) and the receiver uses the concept of time-of-arrival (TOA). Therefore the correspondent range is evaluated by multiplying the light speed with the delay amount that the transmitted GPS signal required to travel from the SV to the receiver.

2.2. Acquisition processes

The GPS receiver is the responsible device for positioning. This task is realized by the acquisition and tracking processes. These are the most important and critical signal processing steps. Acquisition is a two-dimensional search in which the peak detection is carried out roughly. It searches for the code phase and the carrier frequency offset, which are respectively due to the travel time and the Doppler phenomena. The figure 1 illustrates a simplified acquisition channel.

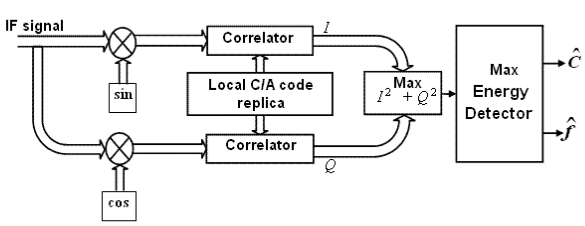

Figure 1: *Simplified acquisition channel*

The IF input signal is obtained from the RF front-end, that precedes the acquisition step. This signal is mixed in quadrature to the carrier frequency replica to convert it to base-band. This is then correlated to the aligned C/A code replica. The I and Q signals are vector summed towards detecting the correlation peak and deducting the time/frequency offsets. Whereas tracking mainly carried out by the well-known lock loops, is the continuous and precise synchronization that refines these acquisition estimations. Note that when a tracking loop looses lock, a reacquisition process is required to reevaluate the new correlation peak location. Assuming that the receiver is searching for a given SV code, the acquisition search space is shown in figure 2. The acquired signal must match for success in two-dimensional. Each range and velocity search increment is called respectively code and Doppler bin, and their combination is a cell.

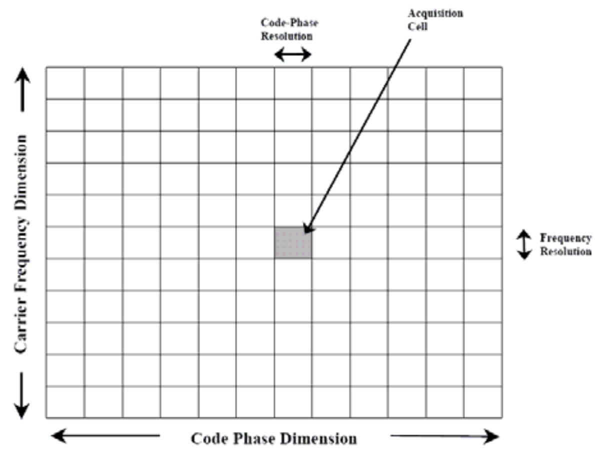

Figure 2: Acquisition search space

The figure 3 illustrates two search methods used at acquisition. Due to the phase code uniform density over its whole period, the used search method as shown in the figure 3.a is rectilinear. This procedure which corresponds to a non-coherent acquisition is called a "cold start". The code period is swept almost entirely to find the corresponding cell to the maximum of energy [6]. The same strategy applies to Doppler offset if no initial information is available about it. Else, its distribution is supposed non-uniform inside the uncertainty region, with a higher probability density close the initial estimate and lower at uncertainty region extremities. The corresponding search procedure called a "warm start" is shown in figure 3.b. This illustrates the search by an increasing dynamic window starting from the initial Doppler estimate cell and advancing in the two directions.

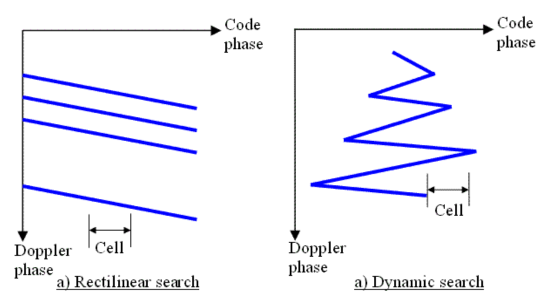

Figure 3: *Acquisition search techniques*

3. UWB OVERVIEW AND MOTIVATING

Ultra wide band has been described by some as one of the most promising communication technologies of our time. Its first milestone started in 1962 by Fontana's work time-domain electromagnetic intended to characterize Linear Time-Invariant

(LTI) systems by ultra-short impulse excitation. Later in 1973, the first UWB communication patent had been established by Ross. More interesting and informative review of pioneer works in UWB can be found in [7]. On February 14, 2002, the FCC amended the Part 15 rules that offer tremendous capacity potential (several Gbps) over short ranges (about 10 meters) at low radiated power (mean EIRP of -41.3 dBm/MHz) in an unlicensed spectrum from 3.1 to 10.6 GHz (see Figure 4). The FCC defines UWB signals as having a fractional bandwidth η greater than 0.25 [2]. This can be expressed by:

$$\eta = \frac{B}{f_c} = \frac{2(f_u - f_l)}{f_u - f_l} \qquad (2)$$

Where B, f_c, f_u and f_l stands respectively for signal bandwidth, center frequency, upper frequency and lower frequency. The UWB signal bandwidth that excesses 500 MHz, is defined as the frequency band bounded by the points that are 10 dB below the highest radiated emission. Table 1 presents the different signal types with regards to their fractional bandwidth definition [8].

Table 2: *Definitions of NB, WB & UWB signals*

Definition \ Signal type	NB	WB	UWB
Fractional bandwidth η	EM waves with Instantaneous bandwidth less than 1% of center frequency (η < 1%)	EM waves with instantaneous bandwidth greater than 1% and less than 25% of center frequency (1% < η < 25%)	EM waves with instantaneous bandwidth greater than 25% of center frequency (η > 25%)

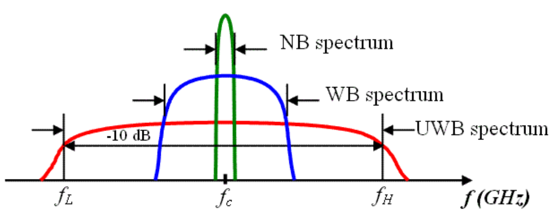

Figure 4: *UWB spectrum*

Such UWB systems rely on ultra-short (picoseconds scale) waveforms that can be free of sine-wave carriers and do not require IF processing because they can operate at base-band. UWB radios come with distinctive advantages that have been appreciated by the radar community for a long time: i) UWB technology does not require a line-of-sight which leads to enhanced capability to penetrate through obstacles; ii) ultra high precision ranging at sub-centimeter level; iii) potential for very high data rates along with a commensurate increase in user capacity; and iv) potentially small size and processing power. Despite these attractive features, interest in UWB devices prior to 2001 was primarily limited to radar systems, mainly for military applications. But things changed drastically in the spring of 2002, when the FCC released a spectral mask allowing (even commercial) operation of UWB over its enormous bandwidth (up to 7.5 GHz). This huge "new bandwidth" opens the door for a great number of bandwidth-demanding position-critical low-power applications [9]. One of the applications that actually can be integrated with UWB communications is positioning [10-12]. Narrowband technology relies on high-frequency radio waves to achieve high resolution. Unfortunately, high-frequency radio wave has short wavelength and cannot penetrate effectively through materials. On the other hand, UWB receiver can time the transmitted pulses to within a few thousand billions of seconds, and still promises good penetration through materials. However, UWB can work as an augmentation to the GPS system giving a better resolution (superior to GPS by three orders of magnitude), thus an offered range resolution in sub-centimeter [13]. Also, as proposed in this paper, UWB can easily be adopted to an indoor (such as underground mining) radiolocation application. Two main properties of UWB make it an attractive choice for any radio implementation: capacity and simplicity. The throughput of a channel is linearly proportional to the bandwidth, so an ultra-wideband system holds the promise of very high-rate communication. Additionally, as UWB is essentially a base-band system, the required analog front-end complexity is less than that for any traditional sinusoidal radio.

3.1. UWB major approaches

IEEE 802.15.3a is considering two different approaches with regard to their allocation of UWB spectrum. Impulse Radio (IR), the traditional approach to UWB communication, involves the use of very short-duration pulses that occupy a single band of several GHz. Data is commonly modulated using pulse-position modulation (PPM); and multiple users could be supported using a time-hopping scheme [14]. Xtreme Spectrum's proposals, similar to two independent IR bands, uses a high chip rate direct sequence spread spectrum (DS-SS) signal to occupy its bandwidth. Compared to the Multiband-OFDM approach, it has greater precision for position location, and realizes better spectrum efficiency. In the Multiband-OFDM coalition approach, the UWB frequency band (from 3.1 to 10.6 GHz) is divided into several smaller bands. Each of these bands must have a bandwidth greater than 500 MHz to comply with the FCC definition of UWB. Frequency hopping between these bands can be used to facilitate multiples access. Companies in the newly formed Multiband-OFDM coalition support this approach primarily because it has greater flexibility in its adaptation to the spectral regulation of different countries and avoids transmitting in already occupied bands. Multibanded UWB, as proposed by the TI/Intel Multiband OFDM coalition, has greater flexibility in coexisting with other international wireless systems and future government regulators, who may choose to limit UWB spectrum allocations to smaller contiguous bandwidths than the US allocation. OFDM is a new and complex multiple access method, but is gaining popularity in WLAN and IEEE 802.11a and 802.16 standards activities. DS-CDMA has better multipath resolution and bandwidth efficiency, and seems more in the spirit of the FCC's original UWB concept, but will likely need a RAKE receiver with considerably more fingers than today's popular CDMA cellphone RAKE which has only a few fingers. DS-CDMA Impulse Radio has already been implemented in working silicon by many companies [15], whereas OFDM has been proven in IEEE 802.11a standard. However, while the TG3a has not yet cast its ballot on these two proposals, it is possible that both standards may survive depending on their related applications. Thus, it is intuitive that DS-UWB approach will be the ideal and appropriate physical layer for our indoor positioning application.

3.2. Pulse Waveform

The main parameter in UWB radio transmissions is the used impulse waveform. The basic theoretical model uses a class of waveforms known as "Gaussian waveforms". The Gaussian pulse waveform is given as:

$$v_g(t) = \exp\left[-(t/\tau)^2\right] \quad (3)$$

Where t and τ are respectively the time and the pulse width. Note that the pulse center frequency f_c is then proportional to $1/\tau$. Another waveform, the Gaussian monocycle, can be created by differentiating the Gaussian pulse. For the Gaussian monocycle, τ is the time between minimum and maximum amplitudes and it defines the time decay constant that determines the monocycle's duration. The expressions for the monocycle pulse and its frequency spectrum are respectively written as:

$$v_m(t) = \frac{t}{\tau}\exp\left[-(t/\tau)^2\right] \quad (4)$$

$$V_m(f) = -j\, f\, \tau^2 \exp\left[-(\tau\, f)^2\right] \quad (5)$$

There are other possible waveforms as pulse like triangular, trapezium and other shaped pulses. However, Gaussian-shaped excitation pulse provides excellent radiation properties [16]. Thus, all commercially available UWB systems use these impulses shape. Figure 5 illustrates the basic Gaussian and monocycle waveforms.

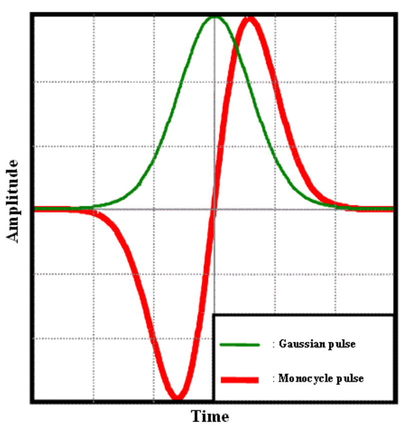

Figure 5: Gaussian & monocycle waveforms

The monocycle shape is the most popular and used impulse by the emerging UWB companies that already developed their own chips, as *PulseON* which is the first commercial UWB implementation made by *Time Domain inc*. Therefore, practical implementation of such Gaussian monocycle remains an important issue. The Gaussian pulse is also commercially used, i.e. by *Aether Wire & Location inc.* on their *localizer* chip, but by coding each transmitted signal bit into two opposite Gaussian pulses. This allows having a balanced-energy-consumption by building such waveform with a null mean value (see figure 6).

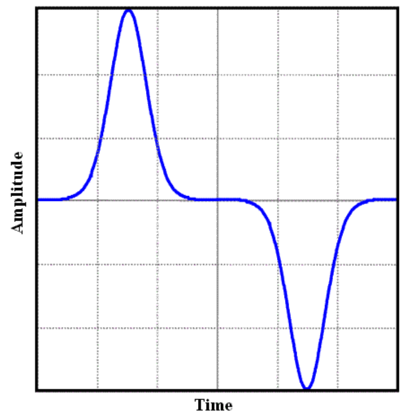

Figure 6: *Balanced Gaussian waveform*

3.3. UWB signal multiplexing

DS-UWB and TH-PPM-UWB are the two multiplexing techniques used in UWB transmissions. With DS-UWB, the UWB signal is transmitted by using DSSS. As in GPS signal, this allows smoothing the transmitted signal's spectrum but do not spread the signal which is already ultra spread-out. The pulse waveform occupies the entire chip interval, thus the duty cycle is 100%. Whereas, obviously the duty cycle in TH-PPM mode is less than 100% and the maximum active users number is defined by the possible positions amount that a pulse can occupy inside a frame [17]. Different TH codes will be assigned to each user sharing the UWB resource. For DS-UWB, gold code can be used as an efficient spreading sequence and again as in GPS system, BPSK can be used to modulate each impulse to its corresponding chip. Therefore, DS-UWB will enable a high data rate in comparison to PPM scheme, while this will intuitively be more immunized to inter-users collision due to the non-uniform spaced impulses used in contrast to DS scheme. This constraint can be easily overcome by the gold code low cross-correlation properties if the users' codes are synchronous. Note that the use of the balanced Gaussian waveform can neutralize noticeably this drawback. The figure 7 shows a DS-UWB transmission example using monocycle BPSK-modulated impulse. By using the widest bandwidth to produce the shortest pulses, DS-UWB supports robust, high-data-rate links in high multipath conditions such as indoor environment and offers precise spatial resolution for location detection [18]. Also, with generating continuous smooth white noise at low level than the other competing approach, DS-UWB minimizes interference. This technique provides scalable performance across a range of application requirements - from high data rates of up to 1Gbit/sec to extremely reduced implementation complexity - while allowing increased scalability, making it ideal for applications such as high-rate data transfers and high-resolution radiolocation in such underground indoor application.

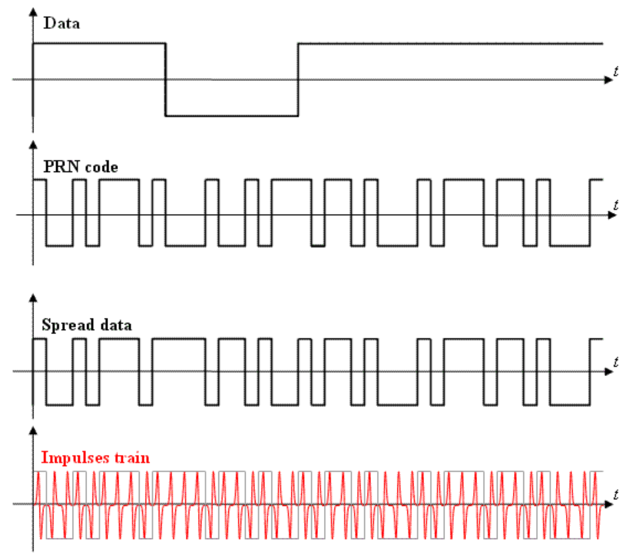

Figure 7: *DS-UWB transmission example*

4. THE PROPOSED SYSTEM

Positioning people (tags) or any mobile object in the underground mining environment can be realized over an Ad-hoc communications structure, where mobile nodes' UWB-radiolocation is applied. The suggested draft is based on a set of reference fixed nodes[1], called verifiers, and with regard to what each mobile node (called claimant) is positioned by using DS-UWB as a physical layer. The well-known multilateration TOA-based (Time-Of-Arrival) distance bounding approach can be used as in GPS. All verifiers that communicate mutually are synchronized to a common clock. Thus if the mobile is considered synchronized to them as well, direct OWR toward these fixed points can be used. The mobile device is then located by evaluating its corresponding ToF (Time-of-Flight) measurements. Note that, as in GPS where the receiver performs pre-synchronization by OWR to its direction, this operation is also required here. However, since the verifiers that should evaluate their distances (radii) with regard to the claimant by the multilateration TOA-based technique, then the appropriate approach will be TWR (Two-Way-Ranging) and the claimant device will need to have a transceiver's architecture. The TWR approach estimates the range using a completely wireless two-way link without a common timing reference. This ranging scheme uses a two-way remote synchronization technique [19]. For this application, the way *claimant-verifiers* is needed for positioning and *verifier-claimant* for pre-synchronization. However, this will increase the necessary mobile device complexity. Therefore, the TDOA (Time-Difference-Of-Arrival) positioning approach is recommended for its capability to compensate this drawback. The advantage of TDOA is that claimant's node positioning does not require communication from the verifiers' nodes to the mobile nodes: the fixed nodes can locate mobile nodes by only precisely measuring signal reception time at each verifier and then computing their corresponding arrival delays to each others. TDOA can perform positioning for a source signal (claimant) in two or three dimensions by finding respectively the intersection of multiple circles (basically three) or spheres (four are enough); based on the time difference of arrival between the signal receptions at multiple verifiers. This corresponds respectively to 2D-trilateration and 3D-quadrilateration. Note that in comparison to the GPS receiver that evaluates itself its position, here the mobile's position is evaluated by the reference array. For a two-dimension positioning, 2D-trilateration with respect to the three neighbors-nodes is proposed. Depending on the mine gallery structure, two or three dimensional positioning is used. The global vision for this suggested radiolocation indoor application is shown in the figure 8. For a two-dimensional positioning case, each mobile's radio signal is collected by its three nearest verifiers' nodes that evaluate its position. Whereas if the gallery structure requires a three-dimensional positioning, another reference array set will be distributed in addition to the used one, *i.e.* over an upper floor, separated to it by *d* and shifted by *d* (see figure 8). This shift means that in this upper floor, the fixed nodes will be located in (0;0), (d;d), (-d;d) and so (see figure 8). Hence for a 3D-positioning, the mobile claimant is located with regard to the six nearest verifiers' nodes that constitute the corners of the 3D-triangle box in which the mobile is located. The verifiers can be smart antennas that can adapt their parameters to the possible situations.

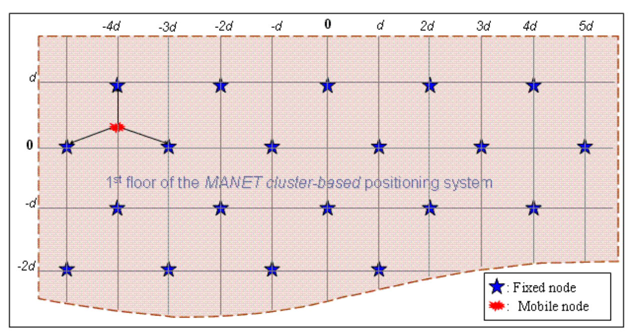

Figure 8: Suggested UWB radiolocation structure

To determine the position of a mobile, each implied reference point measures its distance to that mobile by using TDOA. The measured distances are then gathered by the authority; the position of the device is then determined by computing the intersection point of the circles centered at reference points with radii equal to the measured distances. Therefore in this suggested positioning system each location's determination is made with regard to a *group* of three or six reference points (respectively for 2D or 3D positioning). Hence, with regard to these radiolocation-implied points (*group*), we call the obtained indoor positioning system as a *cluster-based MANET*. In

[1] Whose positions are known.

comparison to GPS, each *cluster* is like a micro-constellation formed by the fixed transceivers' points that carry out the mobile's position claimant. However the receiver part complexity is significantly reduced than the used one in the GPS receiver, due to the need to synchronize only in time. Indeed, UWB's carrier-free particularity will imply a base-band processing structure that estimates the range.

5. CONCLUSION

The new suggested radiolocation system is distinguished by many advantages. Indeed, its simplicity, flexibility and convenience towards integration in an indoor mining environment make it a well-suited positioning solution for such application. UWB use as a physical layer is certainly much beneficent for its high resolution for positioning and its capabilities of materials penetration; hence a LOS (Line-Of-Sight) is not needed for such radio signal. In terms of complexity and cost, this technique is very advantageous. The corresponding acquisition system is characterized by its simple and compact architecture due to UWB's carrier-free characteristic. Therefore, this positioning method is regarded as being a potential solution to locate people and machines in a mine gallery.

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