Experimental Impulse Radio IEEE 802.15.4a UWB Based Wireless Sensor Localization Technology: Characterization, Reliability and Ranging

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Abstract — **Ultra Wide Band (UWB) wireless transmission has recently been the object of considerable attention in the field of next generation location aware wireless sensor networks (WSNs). This is due to its fine time resolution, energy efficiency and robustness to interference in harsh environments. This paper presents a thorough applied examination of prototype IEEE 802.15.4a impulse UWB transceiver technology to quantify the effect of line of sight (LOS) and non line of sight (NLOS) ranging in real indoor and outdoor environments. The results included draw on an extensive array of experiments that fully characterize the 802.15.4a UWB transceiver technology, its reliability and ranging capabilities for the first time. The goal of this work is to validate the technology as a dependable wireless communications mechanism for the subset of sensor network localization applications where reliability and precision positioning are key concerns.**

Keywords — **Ultra Wide Band, Two Way Ranging, Reliability, LOS, NLOS**

I Introduction

Ultra Wide Band 802.15.4a transceiver technology is emerging as an ideal fit for the requirements of the next generation wireless sensor network [1]. IEEE has recognized the need to standardize UWB technology for use in personal area networks (PANs) and has established the IEEE 802.15.4a standard specifying a new UWB physical layer for WSNs [2]. For some WSN applications such as tracking missing persons after an earthquake, sensing data without knowing its sensor location is meaningless. Thusly, real-time localization is becoming a more important concept in WSNs. Accurate range-based localization depends on a precise ranging measurement of the wireless sensor systems. Some classical ranging techniques include received signal strength (RSS), angle of arrival (AOA) and time of arrival (TOA) which are related to energy, direction and the timing of the wireless signals traveling between two sensor nodes respectively. However, UWB techniques employing RSS methods can not obtain accurate ranging estimates due to its strong dependance on the channel parameters, which makes the received energy more sensitive to distance changes in NLOS areas. AOA methods can facilitate accurate ranging when the UWB signal bandwidth is increased, but it needs multiple antennae that makes system larger and costly. TOA parameter based methods provide more accurate range estimates but lower cost compared to the RSS and AOA. The IEEE 802.15.4a standard based on an impulse UWB signal supports a TOA ranging mechanism [3]. Employing prototype fully IEEE 802.15.4a compliant transceiver technology, the world's first IEEE 802.15.4a UWB wireless packet was transmitted and successfully coherently received in real time in March 2009 [4]. This impulse UWB prototype transceiver technology can easily be placed in the next generation Wireless WSN category.

The goal of this paper is to examine the characterization, reliability and ranging precision of an impulse UWB based transceiver for both indoor and outdoor environments. A two way ranging algorithm based on TOA employed as part of this work is described in detail. A theoretical analysis of impulse UWB radio for wireless communication and ranging is provided employing the Shannon Hartley theorem [5] and Cramer-Rao lower bound (CRLB) [6] method.

To fully test the reliability of the UWB ranging system, a distance measuring experiment is firstly implemented in an indoor environment to investigate the case of LOS with multi-path, and also the case of NLOS with different materials, for instance, chair, counter, door and walls; secondly, the outdoor open field case is evaluated with reflections are presented at the receiver. Relevant UWB signal characterization, pulse response and transmitting power are measured. A realistic two way ranging model of the system in operation is described. Finally some conclusion are included.

II Theoretical analysis of UWB ranging

A classical time of arrival based method called two-way ranging (TWR) was originally proposed in [3]. The practical ranging demonstration is described in Fig.1. The leader observes a round trip

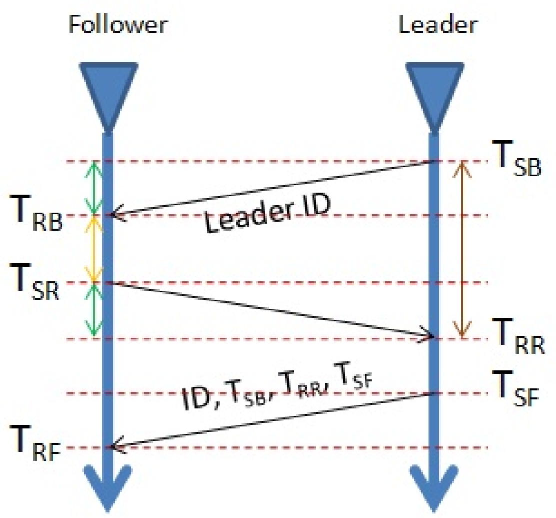

Fig. 1: TW-Ranging Method

time $L_{RT} = T_{RR} - T_{SB}$ and a turn around time $L_{TA} = T_{SF} - T_{RR}$, where T_{SB}, T_{RR} and T_{SF} are the leader send-time, receive-time and future send -time respectively. The follower observes a round trip time $F_{RT} = T_{RF} - T_{SR}$ and a turn around time $F_{TA} = T_{SR} - T_{RB}$, where T_{RB}, T_{SR} and T_{RF} are the follower receive-time, send-time and future receive-time respectively. The value of transmission time T is computed at both leader (T_l) and follower (T_f):

$$2T_l = (T_{RR} - T_{SB}) - (T_{SR} - T_{RB}) \quad (1)$$

$$2T_f = (T_{RF} - T_{SR}) - (T_{SF} - T_{RR}) \quad (2)$$

The follower or leader can then combine these two resultant round trip times (by averaging) to remove by effects of clock differences. The result is then divided by 2 to get one way trip time.

$$T = \frac{2T_l + 2T_f}{2 \times 2} \quad (3)$$

Thus the distance between the two prototypes is:

$$d = T \times C \quad (4)$$

Here C is the speed of light.

When implementing this ranging method in a practical operation, reliable ranging depends on the system being able to accurately determine the transmitting and receiving times of the signal messages at the antenna. The IEEE 802.15.4a specifically defines the time stamps reflecting the instant time of the first ultra wide band pulse of the first bit of the physical layer header (PHR)of a ranging frame. Moreover, there are a number of challenges that remain before accurate ranging can be achieved in a harsh environment including multipath, radio interference, and the NLOS propagations. Thus, the TWR requires that the radio frequency (RF) signal should have a good channel capacity and be robust to interference to enable the detection of the first path of the received signal.

For any given RF radio, Shannon's theory [5] examines the characterization of the signal channel.

$$C = B \times \log_2(1 + SNR) \quad (5)$$

In equation (5), C is the maximum channel capacity, B is the channel bandwidth, and SNR is the signal to noise ratio. This equation indicates that for high frequency bands, large channel capacity is available despite a reduction in transmission power. An UWB signal is defined by the FCC to have either a signal bandwidth exceeding 500MHz or a fractional bandwidth exceeding 0.2. If both UWB (500MHz) and narrow band signal such as IEEE 802.11n [7] (40MHz) have the same SNR, the channel capacity of UWB is approximately 12 times larger than IEEE 802.11n.

UWB signal is broadly categorized into impulse UWB and multi-carrier UWB. The UWB pulse can be easily generated from a Gaussian pulse and its derivatives. A Gaussian pulse in the time domain is described in [8] as:

$$P(t) = \pm \frac{\sqrt{2}}{\alpha} e^{-\frac{2\pi t^2}{\alpha^2}} \quad (6)$$

Here

$$\alpha^2 = 4\pi\sigma^2 \quad (7)$$

where α is the pulse form factor and σ^2 is the variance. The Gaussian pulse and its first 15 derivatives are shown at Fig.2. These pulses are not directly used for practical applications because of the need to meet the spectrum as mandated by the FCC. The first pulse is a Gaussian monocycle.

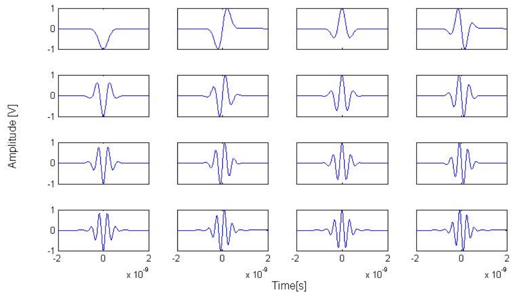

Fig. 2: The Gaussian pulse and its derivatives

From equation 6, it is clear that the bigger the α value is, the narrower the pulse width, but the wider the frequency bandwidth. When the order of the Gaussian pulse derivative increases, its peak frequency increases as indicated in Fig.3.

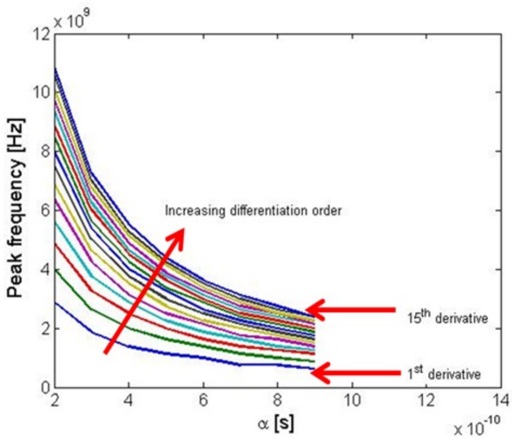

Fig. 3: 15 order derivative verus pulse Peak Frequency and α

It is most likely that signals formed by pulses with duration on the order of fractions of nanoseconds will be UWB signals. This paper is specific to impulse UWB.

The impulse UWB signal can be modulated by Time-Hopping (TH) modulation and Direct Sequence (DS) modulation. The DS modulation is selected to generate a UWB signal whose transmitting signal is indicated as follows:

$$S(t) = \sum_{j=-\infty}^{+\infty} d_j P(t - jT_s) \tag{8}$$

Here, j is integer, d_j is the pseudo random sequence, T_s is the pulse duration, $P(t)$ is signal pulse. A simulation of a DS UWB signal is shown in Fig.4, pulse repetition period $2e^{-9}$s, 10 pulses per bit, periodicity of the DS code is 1 0, and

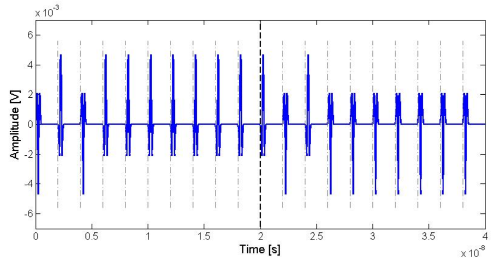

Fig. 4: Direct Sequence UWB Signal Simulation

pulse duration is $0.5e^{-9}$s. From equation 8 and Fig.4, the UWB system architecture is simpler when compared to the Direct Sequence Spread Spectrum (DS-SS) system with Binary Phase Shift Keying (BPSK) carrier modulation. The discrete UWB signal is narrow in width and can be distinguished from multi-path reflections, making accurate pulse timing more strength when compared with conventional RF radios for indoor environments.

For ranging applications, the system captures the transmitting time employing the time of arrival method. The Cramer-Rao lower bound states that the variance of any unbiased estimator would not be lower than the inverse of the Fisher information. Where the Fisher information is defined as a way of measuring the amount of information that an observable random variable X carries about an unknown parameter θ upon which the probability of X depends. The CRLB for impulse UWB signal time delay estimate is given by Kay [6] as follows:

$$Var(\tau) \geq \frac{1}{SNR \times \beta^2} \tag{9}$$

In the equation 9, τ is the transmission time, SNR is the system signal to noise ratio, and β is the effective bandwidth. Therefore, the wider the signal bandwidth or the better the SNR, the more accurate the ranging precision.

An Impulse UWB (500MHz) is therefore a promising technology for location aware sensor networks, due to its high quality communication and accurate ranging. Owing primarily to the fine time resolution on the order of sub-nanosecond pulses, accuracy of a few centimeters in distance measurement can be obtained.

III Experimental Activities

The goal of this experiment is to validate the characterization, reliability and ranging of the UWB transceiver technology in indoor and outdoor environments. The measurements were made using two FCC-compliant UWB radios obtained from Decawave, a company based in Dublin, Ireland[9]. The primary focus is to characterize the electrical properties of these UWB transceivers. The two radios, a leader and a follower, each of which is 15cm wide and 30cm high, generate impulse UWB signals resulting in a signal with a bandwidth of 500MHz and a center frequency of 4GHz.

In the system configuration, a Pulse Repetition Frequency (PRF) of 16MHz, a preamble length of 1024, preamble code 4 and data rate 850kbit/s are selected for both transceivers. The system delay which is the key factor for ranging measurement is tested and determined to be 277.850ns. However, the system delay may need to be tuned if operating modes are changed, for instance, the delay needs to be changed down when increasing the PRF value. Large system delays will lead to the time of arrival being a negative value. The prototype has no Automatic Gain Control (AGC) unit, thus setting of the transmission attenuation value is needed which is 13.5dB to ensure the transmitting power is compliant with the FCC emission limits.

The UWB radio signal spectrum captured by an agilent spectrum analyzer is shown as Fig.5. The effective bandwidth is about 500MHz, from a lower frequency of 3.75GHz to an upper frequency of 4.25GHz, is observed with 1MHz resolution bandwidth. The Power Spectrum Density(PSD) is approximately -41.3dBm/MHz which meets with FCC emission limits in Fig.6. The band power is measured as -13.31dBm at the 4.22GHz point, from which, the antenna gain is calculated, resulting in a value of 3.1 and the transmitting power is about 0.047mW. The TWR ranging algorithm

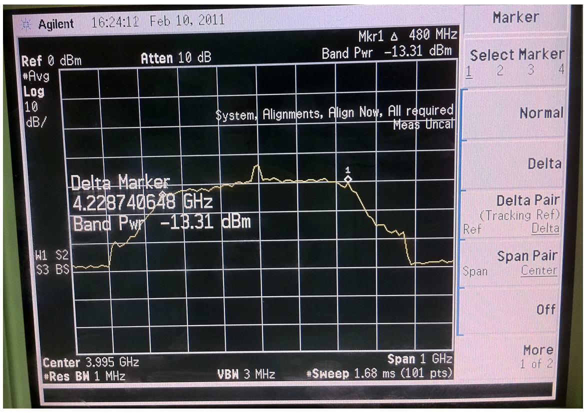

Fig. 5: UWB Signal Spectrum

(equation (1),(2),(3),(4)) is embedded in the system IC for each of the prototype boards. Successful ranging relies on the system being able to accurately determine the transmitting and receiving times of the signals as they leave one antenna and arrive at the other antenna. Due to the digital hardware that makes the generation or reception of the ranging marker which is the first bit of the PHR, the adjustments are needed to add the transmitting system-to-antenna delay to the transmitting time-stamp and subtract the re-

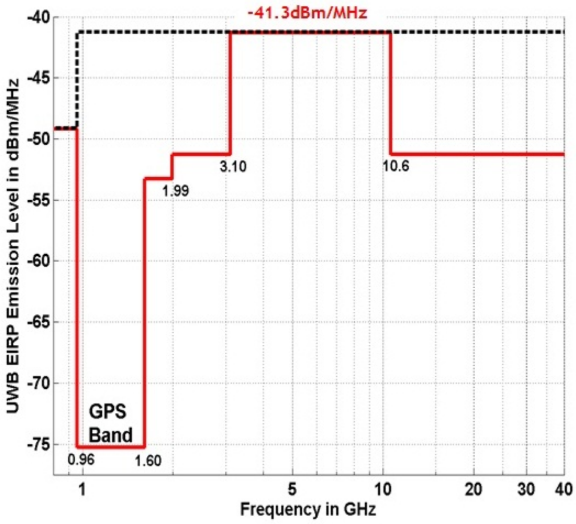

Fig. 6: Indoor Emission Mask

ceiving antenna-to-system delay from the receiving time-stamp. The first path arrival time is determined from the channel impulse response data read from the register and the time delta thus determined is added. The time delta is the distance between the time stamp window index, as indicated by the first byte of channel response read, and the software determined leading path which is the sample index or point between two indices where the software determines the first arriving signal to be. The system delay as previously specified is added. Compensation for the clock offset is achieved by adding the relevant offset. Thus, the realistic two way ranging model based on the original TW ranging protocol[3] based on equation 1 and equation 2 should be as follows:

$$2T = T_{RTT}^{L} - T_{TAT}^{F} \qquad (10)$$

Where

$$T_{TAT}^{F} = T_{DELAY} - A_F^R + Lp_F^R + T_{off}^F + A_F^T \qquad (11)$$

$$T_{RTT}^{L} = A_L^T + T_{TAT}^F - A_L^R + Lp_L^R + T_{off}^L \qquad (12)$$

In equation(10), T_{RTT}^{L} is the round-trip-time of the leader, T_{TAT}^{F} is the turn around time of the follower. In equation(11) and (12), the T_{DELAY} is the specified time delay, A_F^R and A_L^R are the receiving antenna-to-system delay at follower and leader respectively; while, A_F^T and A_L^T are the transmitting system-to-antenna delay at follower and leader respectively; Lp_F^R and Lp_L^R are the first path detection delay of the follower and the leader; T_{off}^F and T_{off}^L are the relevant time offset at both follower and leader respectively. Thus, the total ranging time is the summation of ranging count and clock offset.

When the system is running well, the channel response can be captured from a ranging GUI as shown in Fig.7, in which the red line (c) is the plot of the real pulse response, the green line (d) is the imaginary response and the blue line (b) is the computed magnitude values. The vertical cyan line (a) is the leading path which is used to find the first in time arriving receive signal. The system SNR (44.4dB), first path SNR (38.4dB), and the real time distance (1.31m) is tested and recorded. This distance is firstly measured in an office with no obstructions and subsequently less reflections. Compared with the true value 1.30m measured physically using a tape, the measured instant and average distances are very accurate with only 1cm error. The round trip time value L, R, of both local and remote prototypes and their average value C are calculated in device time units [3]. The device time units follow the definition of time contained in the IEEE Std 802.15.4a, which states the LSB of a time value represents 1/128 of a chip time at the mandatory chipping rate of 499.2MHz. After dividing C by 128 and multiplying by the speed of light, the distance is finally calculated.

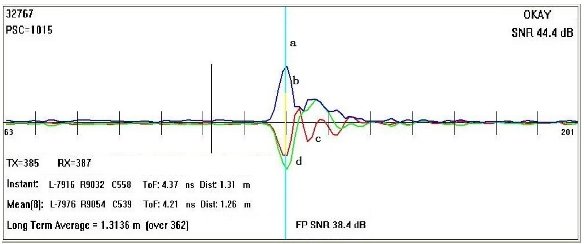

Fig. 7: Received UWB Signal Response

IV EXPERIMENTAL RANGING RESULTS

To validate the reliability of the UWB transceiver ranging in cluttered indoor and outdoor environments, according to the different channel models, 3 scenarios are defined and implemented in some offices, hallways, and yards in the Tyndall National Institute as shown in Fig.8. The two motes are mounted on the floor, One is located at the fixed origin, while the other moves to perform point-to-point measurement. The distance between the two radios is varied from 1m up to 45m to capture a variety of operating conditions. In each measurement location, the values such as the pulse response, instant distance estimates, SNR, as well as the actual distance from a tape are recorded.

a) LOS Test

The line of sight ranging experiments are conducted in a library, an indoor hallway, an outdoor hallway and in the open field such as Fig.8(a,b) where is no obstructions between the two motes. This experiment is to validate the performance of the UWB ranging system in an environment with significant multi-path propagation, thermal noise and narrowband interference such as WIFI signals. Testing Points are placed randomly but are restricted to the tape measured points.

(a) Outdoor LOS (b) Indoor LOS (c) Soft NLOS (d) Hard NLOS

Fig. 8: LOS, Soft-NLOS, Hard-NLOS Ranging Campaigns

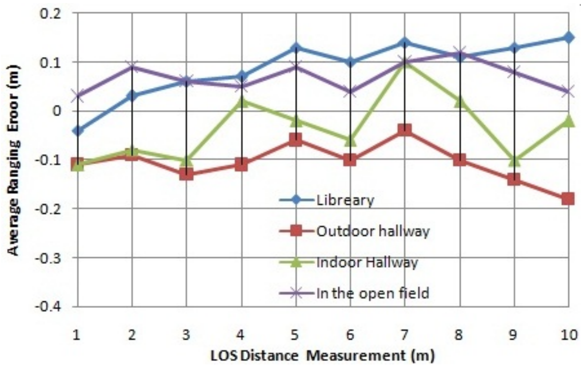

Fig. 9: Ranging Results of LOS Area Measurement

Fig.9 shows the average LOS ranging results in the library which has some counters and chairs around the motes, the outdoor hallway in which the two boards are located between the outside walls and bicycle shed, the indoor hallway with some doors, WIFI sites and walls on the both sides and in the open field where there are no obstructions, and the only sources of signal reflection are the operators, the equipment and the ground. The average ranging errors of these tested points are less than ±20cm regardless of the system error. The errors measured in the open field are less than 10cm, which is more accurate than the results of other conditions with more reflections and sources of interference in between. The outdoor hallway result is less than the positive value measured via a tape, that is likely because the PHY header check bits of some frames were in error.

b) Soft-NLOS Test

This experiment aims to validate the reliability of the UWB ranging system through a Soft-NLOS channel which occurs when the LOS path is obstructed by materials with relatively low attenuation or by a combination of these materials such as glass, chairs, counters and doors. A 3m testing point is selected for each experimental cluster and different obstructions are deployed between the two motes as in Fig.8 (c). Some obstructions are combined as this would likely be the case in actual conditions. All the results of clusters in Fig.10 show that the error from different obstructions varies from 6cm (Glass) to 29cm (Door). These experimental conditions represent the most common channel model over the distances of interest in most European offices, the average results of less than 30cm accuracy are acceptable to validate that the UWB signal can be utilized in indoor ranging measurements.

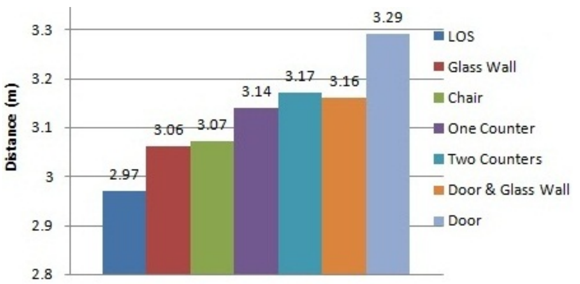

Fig. 10: Ranging Results of Soft-NLOS Area at 3m Point

c) *Hard-NLOS Test*

This experiment (Fig.8 (d)) attempts to validate the capability of the UWB ranging system in a hard-NLOS channel with multiple concrete walls or multi-obstructions in the environment. Results in Fig.11 indicate that hard obstructions severely attenuate the UWB signal propagation and generate large positive bias in the range estimates. The distance error varies widely from 26cm for one wall to 87cm for 4 walls. While at the 38m point, the receiver is unable to receive the signal. It is clear that localization in this hard NLOS rooms can not obtain high precision by only using TWR algorithm. Some method and algorithms [3] are proposed to improve or solve the hard NLOS ranging problems, but ranging in an NLOS area is still a challenging problem for indoor locations.

Fig. 11: Ranging Results of Hard-NLOS Area

V Conclusion

In this paper, we theoretically analyzed and realistically validated the reliability of an impulse UWB transceiver based point-to-point ranging system using a two way ranging algorithm in both indoor and outdoor environments. In theory, the UWB signal is very resistant to multi-path and reflections, the CRLB method proves that the UWB signal has a high precision on the order of several centimeters. In practical operation, the two UWB transceivers were evaluated in this study satisfying the FCC limits. A realistic two way ranging model was generated with antenna-to-system delay, first path detection delay and time offset and implemented in the ranging system. Results recorded of LOS, Soft-NLOS and Hard-NLOS ranging experiments show that UWB transceivers are capable of capturing accurate transmission time between two radios which can be used in turn to compute the real distance. With features such as large channel capacity, robustness to interference and multi-path, energy efficiency and fine resolution, UWB transceiver technology is a dependable wireless communications mechanism for WSN localization applications.

References

[1] M.G. diBenedetto, T. Kaiser, A.F. Molish, I. Oppermann, C. Plitano, and D. Porcino (eds.). "UWB Communications Systems: A Comprehensive Overview". *EURASIP Publishing*,2005.

[2] IEEE Working Group 802.15.4a. "Draft specifications for IEEE 802.15.4a standard".

[3] IEEE Std 802.15.4a^{TM}-2007, IEEE Standard for information Technology

[4] http://www.idtechex.com/events/presentations/scensor_an_ieee802_15_4a_uwb_compliant_chip_ripe_for_energy_harvesing_001824.asp

[5] Kazimierz Siwiak and Debra McKeown. "Ultra-Wideband Radio Technology". John Wiley and Sons,2006.

[6] S.M. Kay. "Fundamentals of Statistical Signal Processing Estimation Theory". *Englewood Cliffs, New Jersey:Prentice-Hall*,1993.

[7] IEEE Std 802.11n-2009,IEEE Standard for information Technology–Telecommunications and information exchange between systems

[8] Maria-Gabriella Di Benedetto and Branimir R. Vojcic. "Ultra Wide Band Wireless Communications : A Tutorial". *Journal of communications and networks, Vol.5, No.4,* , December 2003.

[9] http://www.decawave.com/index.html