Paper

DS-UWB and TH-UWB Energy Consumption Comparison

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Abstract—The energy consumption of the wireless communication systems is starting to be unaffordable. One way to improve the power consumption is the optimization of the communication techniques used by the communication networks and devices. In order to develop an energy efficient UWB multi-user communication system, the choice of modulation and multi access technique is important. This paper compares two Ultra-wideband multi-user techniques, i.e. the DS-UWB and the TH-UWB in the case of the Nakagami-m fading channel. For the DS-UWB technique, the orthogonal (T-OVSF, ZCD) and non-orthogonal (Kasami) codes are used. For TH-UWB, authors consider different modulations (PPM, PSM, PAM). This comparison allows choosing the best solution in terms of energy consumption, data rate and communication range. Two different studies are realized to find the most efficient technique to use. In the first study, the same number of users for the different type of codes (data rate values) is chosen and the total energy consumption for several distances and path-loss coefficient is computed. In the second one, the multiusers effects (same data rate) for various values of distances and path-loss are evaluated.

Keywords—energy consumption, multi-user techniques, Nakagami-m fading channel, TH time hopping, UWB.

1. Introduction

Ultra-wideband (UWB) [1] is a radio technique that offers the ability to create efficient energy and low complexity communication systems, at limited cost. This energy efficiency is called green communication [2]. Researchers have already explored various subjects related to energy efficiency from system design to network protocols. In [3], the authors present an energy-efficient low complexity pulse generator for an UWB system in CMOS technology. In [4], a low power UWB transmitter with the digital pulse generator and binary phase modulator also built in CMOS chip is proposed. Authors in [5] describe a new IR-UWB receiver capable of achieving remarkable energy saving. They are operating in the lower, 3.1 to 4.5 GHz, UWB frequency band allocated in some regions of the world. Reference [6] introduces and analyses an efficient energy adaptive transmission protocol called ATP-UWSN for UWB Wireless Sensor Networks. This protocol adapts the error-control code rate and the spreading code length to match the Channel State Information (CSI), therefore reaching optimum communication parameters. Paper [7] considers an energy-aware and link-adaptive strategy for UWB WSNs to introduce different routing metrics. In [8], the authors take advantage of the positioning capabilities of UWB to propose an energy efficient routing algorithm. This algorithm is developed to search for energy efficient routes with respect to the Quality of Service (QoS) of the system. In [9] and [10] two well-known UWB modulations are compared, M-ary Pulse Position Modulation (MPPM) and M-ary Pulse Amplitude Modulation (MPAM), in the AWGN channel and the Nakagami-m fading channel respectively. The authors showed in both that the efficient technique has to be determined with respect to the transmission scenario and that generally MPPM is less energy consuming than MPAM for high constellations and long communication ranges. These results were obtained for a communication link with only one active user.

As a supplementary contribution to [9], [10], in this paper, authors study the energy efficiency of multi-user techniques for UWB systems. For this comparison, two largely used UWB multi-users techniques are selected, i.e. the Direct Sequence UWB (DS-UWB) and the Time Hopping UWB (TH-UWB). So, the purpose of this work is to compare two multi-user methods to identify the less energy consuming technique according to some operational constraints. Moreover, in this work, an energetic model is developed for two UWB multi-user techniques in Nakagami-m fading radio channels respectively. The aim is to find the most efficient UWB-multi-users technique for different transmission scenarios as a function of the communication range and of the associated path-loss attenuation. Nakagami-m distribution is used in UWB to model the multi-path components (MPCs) in the IEEE 802.15.4a [11]. To authors' knowledge there is no energetic model based on this distribution to estimate the energy consumption of UWB multiuser systems.

The paper is organized as follows. In Section 2 a brief definition of direct spreading DS-UWB and time hoping TH-UWB is presented. The system model and the channel description are shown in Section 3. The different multiple user techniques are presented in Section 4. Section 5 compares the results. Section 6 concludes the paper and gives some perspectives.

2. UWB Multi-User Techniques Description

To support multi-users transmission in UWB, the two well-known techniques are used, which are the DS-UWB and the TH-UWB. In the DS-UWB, authors often use BPSK to modulate the transmitted signal. However, for the TH-UWB, several techniques such as PPM, PAM and PSM or BPSK-PSM (combination of two modulations) are used. In the following, the two multi-access techniques with these respective modulations are described.

2.1. DS-UWB

An UWB DS-UWB signal can be written as [10]

$$S_{DS}^{(k)}(t) = \sqrt{\frac{E_b}{N_c}} \sum_{j=-\infty}^{+\infty} \sum_{n=0}^{N_c-1} d_j^{(k)} c_n^{(k)} p\big(t - jT_f - nT_c\big) . \quad (1)$$

In Eq. (1), $S_{DS}^{(k)}(t)$ represents the signal of the k-th user, $p(t)$ is the UWB pulse, which is normalized to satisfy $\int_{-\infty}^{+\infty} p^2(t)dt = 1$. The other parameters in the signal definition can be described as:

- $\sqrt{\frac{E_b}{N_c}}$ is a normalization factor to make all considered systems having the same per bit energy noted E_b;
- N_c is the number of chips used to transmit one bit of information;
- $c_n^{(k)}$ is the unique spreading sequence allocated to each k-th user; its values are set from $-1 \ldots 1$;
- T_f is the frame duration and is the chip duration satisfying $T_f = N_c T_c$;
- T_b is the bit duration; in this paper, $T_b = T_f$;
- $d_j^{(k)}$ is the data bit information; its values are from $-1 \ldots 1$ (the BPSK for modulation is used).

In this work, the different orthogonal codes are used: the ternary Orthogonal Variable Spreading Factor (T-OVSF) [11], Zero Correlation Duration (ZCD) [12] and non-orthogonal codes Kasami Type 1 [13] as spreading sequence techniques.

2.2. TH-UWB

TH-Pulse Position Modulation (PPM), an UWB TH-PPM signal can be written as [10]:

$$S_{TH\text{-}PPM}^{(k)}(t) = \sqrt{\frac{E_b}{N_s}} \sum_{j=-\infty}^{+\infty} p\big(t - jT_f - c_j^{(k)} T_c - d_{j/N_s}^{(k)} \delta\big) . \quad (2)$$

In Eq. (2) $S_{TH\text{-}PPM}^{(k)}(t)$ represents the signal of the k-th user, $p(t)$ is the UWB pulse, which is normalized to satisfy $\int_{-\infty}^{+\infty} p^2(t)dt = 1$. The other parameters in the signal definition are:

- N_s is the number of pulses used to transmit an information bit; it is also called the repetition code;
- $C_j^{(k)}$ represents the time hopping (TH) code; it is a pseudorandom variable bounded by $0 \le c_j^{(k)} \le N_h$, where N_h is the hop count;
- T_c is the hop width satisfying $T_f = N_h T_c$;
- $T_b = N_h T_f$ in TH-UWB systems;
- δ is the PPM modulation parameter and $d_{j/N_s}^{(k)}$ is the data bit information that takes values from range $0 \ldots 1$.

In TH-BPSK-Hybrid BPSK and Pulse Shape Modulation (PSM) an UWB TH-BPSK-PSM signal can be written as:

$$S_{TH\text{-}BPSK\text{-}PPM}^{(k)}(t) = \sqrt{\frac{E_b}{N_s}} \sum_{j=-\infty}^{+\infty} d_{j/N_s}^{(k)} p_{MHP}\big(t - jT_f - c_j^{(k)} T_c\big) ,$$

where:

- $p_{MHP}(t)$ is one of the possible Modified Hermite Pulses (MHP) defined in [16]. To generate MHP waveforms, the following recurrence relation is used:

  $$h_n(t) = (-1)^n e^{\frac{t^2}{4}} \frac{d^n}{dt^n} e^{\frac{-t^2}{2}} .$$

  Therefore, MHPs for $n = 0, \ldots, 3$ are:

  $$h_0(t) = e^{\frac{-t^2}{4}} ,$$
  $$h_1(t) = t e^{\frac{-t^2}{4}} ,$$
  $$h_2(t) = (t^2 - 1) e^{\frac{-t^2}{4}} ,$$
  $$h_3(t) = (t^3 - t) e^{\frac{-t^2}{4}} .$$

- $d_{j/N_s}^{(k)}$ is the data bit information and takes values from $-1 \ldots 1$.

In systems using TH-Pulse Amplitude Modulation (PAM) an UWB TH-PAM signal can be written as:

$$S_{TH\text{-}PAM}^{(k)}(t) = \sqrt{\frac{E_b}{N_s}} \sum_{j=-\infty}^{+\infty} p\big(t - jT_f - c_j^{(k)} T_c\big) .$$

3. Model and Channel Description

3.1. The Model

In order to study the energy consumption of a UWB system, the architecture of the adopted transmitter and receiver shown in Fig. 1 was used. The P_{pg}, P_{pa}, P_{filt}, P_{ADC}, P_{LNA}, P_{mix}, P_{int} and P_{filr} are the power levels of pulse generator, power amplifier, transmitter filter, digital to analogue converter, analogue to digital converter, low noise amplifier, mixer, integrator, and receiver filter respectively.

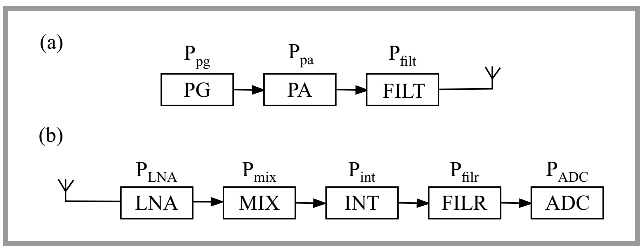

Fig. 1. Block diagram of used: (a) transmitter, (b) receiver.

Sending a sequence of N bits requires T time. Usually, the transceiver is assumed to work according to three different operating modes:

- active mode – in this mode the information is transmitted. The time spent by the transceiver in this active mode is noted T_{ac}. All the components are consuming power;
- sleep mode – when there is no information to convey, the system enters a sleep mode. The time spent by the transceiver in this sleep mode is noted T_{sl}. In this case, a restricted number of components are active;
- transient mode – this corresponds to the transition mode between the sleep and the active modes. The time spent by the transceiver in this transient mode is noted T_{tr}.

Thus, T can be written as:

$$T = T_{ac} + T_{sl} + T_{tr}\,. \tag{3}$$

In paper [17], the authors did not take into account the time to shift from active to sleep mode because it is usually very fast compared to the shift from sleep to active mode. However, they still consider the amount of time spent by the system to shift from sleep to active mode due to the use of a frequency synthesizer, which is energy consuming when the transition takes place. For the UWB Impulse Radio technique, the synthesizer is not used. So, this transient time is not considered. Therefore, the energy needed to transmit N bits is given by Eq. (4):

$$E = P_{ac}T_{ac} + P_{sl}T_{sl}\,, \tag{4}$$

where P_{ac} and P_{sl} represent the power consumption during the active mode and the sleep mode respectively. The power consumption of the active mode includes the transmission power P_t and the electronic circuitry power consumption P_c. P_c combines the receiver power consumption noted P_{cr}, and the transmitter power consumption noted P_{ct}. In the transmission part, the power consumption of Power Amplifier (PA) is linked to the overall transmission power by: $P_{pa} = \alpha P_t$, where $\alpha = \frac{\xi}{\eta - 1}$, ξ is the average of peak to ratio and η is the drain efficiency of the PA. These variables depend on the class of the amplifier and the selected modulation scheme. As compared to the power consumption in the active mode, the power consumption in the sleep mode is very low. Therefore, in this study, $P_{sl} = 0$ i assumed. However, it could be considered for specific applications necessitating long periods in sleep mode. Finally, the amount of energy needed to transmit one bit of information is given in Eq. (5):

$$E_T = \frac{\lfloor (1+\alpha)P_t + (P_c - P_{pa}) \rfloor T_{ac}}{N}\,. \tag{5}$$

3.2. Channel Description

For the sake of simplification, a number of parameters of the IEEE 802.15.4a standard [10] is used and a Nakagami-m distribution for the radio propagation channel amplitudes is adopted. This was integrated in the standard with the UWB path-loss model as described below. Usually the IEEE 802.15.4a uses a clustering behavior for the MPCs. In each cluster there are several rays, the arrivals of the clusters and the rays are modeled as Poisson process. In this model, a deterministic model is used where the MPCs are spaced by the same duration of time τ, and the channel can be written as

$$h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - l\tau)\,,$$

where α_l is the path amplitude. It was shown in [18] that the two models provide almost the same results. This channel model proves to be sufficient for presented analysis. Moreover, the channel gain for a z-th path-loss channel using a distance d between the transmitter and the receiver is

$$G_d = \frac{P_t}{P_s} = G_1 M_l d^z\,.$$

In this expression:

– P_s and P_t are the received power (energy per symbol) and the transmitted power respectively,

– M_l is the gain margin,

– $G_1 = \frac{(4\pi)^2}{g_t g_r \lambda^2}$ is the channel gain for $d = 1$ m which can be obtained from the transmitter and the receiver antenna gains g_t and g_r and from the free space wavelength λ.

Thus, the instantaneous SNR is $\gamma_l = \dfrac{\alpha_l P_t}{G_d N_0 B}$, and the average SNR is $\overline{\gamma_l} = \dfrac{\Omega_l P_t}{G_d N_0 B}$ with $\Omega_l = E\lfloor |\alpha_l^2| \rfloor$.
In this case, the power density function of the instantaneous SNR is:

$$f_\gamma(\gamma_l) = \frac{m^m \gamma_l^{m-1}}{\overline{\gamma_l}^m \Gamma(m)} e^{\frac{-m\gamma_l}{\overline{\gamma_l}}}\,.$$

The path-loss in UWB is modeled as a normal distribution $z(\mu_z, \sigma_z)$ with $z = \mu_z + n\sigma_z$ and $n = -0.75 \ldots 0.75$ [19]. The path-loss mean and variance values change if the transmitter and the receiver antennas are within Line of Sight (LOS) or within Non Line of Sight (NLOS) conditions. The corresponding statistics are presented in Table 1.

Table 1
Path-loss statictics

	LOS		NLOS	
	μ_z	σ_z	μ_z	σ_z
z	1.7	0.3	3.5	0.98

4. Energy Efficiency Analysis

4.1. DS-UWB with Orthogonal Codes

The chip duration is $T_c = aT_p$ where T_p is the pulse duration and bit duration $T_b = T_f = N_c T_c$. The duration of the active mode $T_{ac} = NT_b$, where N is the length of the data sequence.

For the sake of simplicity, it is assumed that presented system is perfectly synchronized. Therefore, the codes are orthogonal and, as a consequence, their cross-correlations are nil.
For such a system, the conditioned BER on the instantaneous SNR is [20]:

$$P_e(\gamma_l) = Q\left(\sqrt{2\sum_{l=1}^{L}\gamma_l}\right),$$

where $SNR = \gamma$. Thus, the average BER for the DS-UWB system using orthogonal codes can be upper bounded by [20]:

$$P_e = \int\int\int_0^{+\infty} P_e(\gamma_l) f_\gamma(\gamma_l) d\gamma_1 \ldots d\gamma_L \leq \frac{1}{2}\prod_{l=1}^{L} I(\overline{\gamma_l}),$$

where $I(\overline{\gamma_l}) = \left(1 + \frac{\overline{\gamma_l}}{m}\right)^{-m}$.
The Maximum Ratio Combining (MRC) technique [21] is used for detection, which is mandatory in a rake receiver. The fading amplitudes are independent and not necessarily identical. In the special case where the L channels are identically distributed with the same average SNR, $\overline{\gamma}$, the BER is simply written as:

$$P_e \approx \frac{1}{2}\left(1 + \frac{\overline{\gamma}}{m}\right)^{-mL}.$$

So, the average SNR can be expressed as $\overline{\gamma} = m\left((2P_e)^{\frac{-1}{mL}} - 1\right)$ with $\overline{\gamma} = \frac{\Omega P_t}{G_d N_0 B}$.
Hence, $P_t T_{ac} = am\left((2P_e)^{\frac{-1}{mL}} - 1\right)\frac{N_0 G_d N N_c}{\Omega}$.
Then, the total energy consumption of the DS-UWB system using orthogonal codes is:

$$E_{DS\text{-}OC} = (1+\alpha)am\left((2P_e)^{\frac{-1}{mL}} - 1\right)\frac{N_0 G_d N_c}{\Omega} + \frac{(P_c - P_{pa})T_{ac}}{N}. \quad (6)$$

For transmission, the same transmitter is used as in the case of an AWGN channel but, for reception, a partial rake receiver using the MRC technique and the following characteristics $P_c = P_{ct} + P_{cr}$ was chosen:

- transmission power: $P_{ct} = P_{pg} + P_{pa} + P_{filt}$,
- reception power: $P_{cr} = P_{LNA} + L(P_{int} + P_{mix}) + P_{filr} + P_{ADC}$,

where L is the number of the rake receiver branches.

4.2. DS-UWB with Non-orthogonal Codes

The difference between non-orthogonal and orthogonal codes relies on the fact that the cross-correlation values are not nil. Thus, the BER cannot be identical to the mono-user case. For a predefined BER $P_e = 10^{-3}$, the interferences caused by the other users can be approximated by a Gaussian distribution. In the literature, the Gaussian approximation does not hold for all SNR values [12], [22], [23] but, in [12] the approximation is almost Gaussian for $P_e = 10^{-3}$. Hence, the signal to interference plus noise ratio (SINR) can be written as follows [11]:

$$SINR = \frac{2\sum_{l=1}^{L}\gamma_l}{1 + \frac{N_u - 1}{N_c}\sigma_{DS}\sum_{l=1}^{L}\overline{\gamma_l}},$$

where $\sigma_{DS} = \frac{1}{T_c}\int\int_{-\infty}^{+\infty}\left[w_{rec}(t) w_{rec}(t-s)\right]^2 ds$, $w_{rec} = \left[1 - 4\pi\left(\frac{t}{T_p}\right)^2\right] e^{-2\pi\left(\frac{t}{T_p}\right)^2}$, N_u is number of users, and N_c is number of pulses.
The conditional BER on the instantaneous SNR can be written as (a special case where the L channels are identically distributed with the same average): $P_e(\gamma_l) = Q\sqrt{2SINR}$.
Thus, the average BER for the DS-UWB system using non-orthogonal codes can be upper bounded by:

$$P_e = \int\int\ldots\int_0^{+\infty} P_e(\gamma_l) f_\gamma(\gamma_l) d\gamma \ldots d\gamma_L \leq \frac{1}{2}\prod_{l=1}^{L} I(\overline{\gamma_l}),$$

where $I(\overline{\gamma_l}) = \left(1 + \frac{\frac{1}{m}}{\frac{1}{\overline{\gamma_l}} + \frac{N_u - 1}{N_c} L\sigma_{DS}}\right)^{-m}$.
So,

$$P_e \approx \frac{1}{2}\left(1 + \frac{\frac{1}{m}}{\frac{1}{\overline{\gamma}} + \frac{N_u - 1}{N_c} L\sigma_{DS}}\right)^{-mL}$$

and

$$\overline{\gamma} = \frac{1}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}} - 1\right)} - \frac{N_u - 1}{N_c} L\sigma_{DS}}.$$

Hence,

$$P_t T_{ac} = \frac{\frac{N_0 G_d N_c N}{\Omega}}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}} - 1\right)} - \frac{N_u - 1}{N_c} L\sigma_{DS}}.$$

The total energy consumption of a DS-UWB system using non-orthogonal codes in Nakagami-m channel with path-loss can be written as:

$$E_{DS\text{-}NOC} = (1+\alpha)\frac{\frac{aN_0 G_d N_c}{\Omega}}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}} - 1\right)} - \frac{N_u - 1}{N_c} L\sigma_{DS}} + \frac{(P_c - P_{pa})T_{ac}}{N}.$$

The consumed powers of the transmission and the reception circuitries are identical to the system using the orthogonal codes.

4.3. TH-BPSK-PSM

In order to evaluate the performance of MHPs, in the same conditions as other multiple user techniques, two different waveforms at least must be used. Therefore, the first MHP is assigned to the first group of 8 users and the second MHP is assigned to the second group of 8 users. TH-BPSK is also the technique used for assuring simultaneous transmission. As the MHP are orthogonal pulses, the interference will mainly be caused by the users belonging to the same group. As in the previous cases, the interference can be approximated as a Gaussian variable for $P_e = 10^{-3}$. The SINR can be written as follows:

$$SINR = \frac{2\sum_{l=1}^{L}\gamma_l}{1+\frac{\frac{N_h}{2}-1}{N_s}\sigma_{BP}\sum_{l=1}^{L}\overline{\gamma_l}},$$

where $\sigma_{BP} = \frac{1}{T_f}\iint_{-\infty}^{+\infty}\left[P_{MHP}(t)P_{MHP}(t-s)\right]^2 ds.$

The conditional BER on the instantaneous SNR can be written as (special case where the L channels are identically distributed with the same average): $P_e(\gamma_l) = Q\sqrt{2SINR}$.

The BER can be upper bounded of this system by writing:

$$P_e = \iint\ldots\int_0^{+\infty} P_e(\gamma_l)f_\gamma(\gamma_l)d\gamma_1\ldots d\gamma_L \le \frac{1}{2}\prod_{l=1}^{L} I(\overline{\gamma_l}),$$

$$P_e \approx \frac{1}{2}\left(1+\frac{\frac{1}{m}}{\frac{1}{\overline{\gamma}}+\frac{\frac{N_h}{2}-1}{N_s}L\sigma_{BP}}\right)^{-mL},$$

$$\overline{\gamma} = \frac{1}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}}-1\right)}-\frac{\frac{N_h}{2}-1}{N_s}L\sigma_{BP}}.$$

Hence,

$$P_t T_{ac} = \frac{\frac{N_0 G_d N_s N_h N}{\Omega}}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}}-1\right)}-\frac{\frac{N_h}{2}-1}{N_s}L\sigma_{BP}}.$$

The total energy consumption by a system using MHP in a Nakagami-m channel is:

$$E_{MHP} = (1+\alpha)\frac{\frac{aN_0 G_d N_s N_h}{\Omega}}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}}-1\right)}-\frac{\frac{N_h}{2}-1}{N_s}L\sigma_{BP}} + \frac{(P_c-P_{pa})T_{ac}}{N}.$$

4.4. TH-PAM

For a BER $P_e = 10^{-3}$, the multi-user interference is approximated by a Gaussian distribution. In this case the SINR is:

$$SINR = \frac{2\sum_{l=1}^{L}\gamma_l}{1+\frac{N_h-1}{N_s}\sigma_{PAM}\sum_{l=1}^{L}\overline{\gamma_l}},$$

where $\sigma_{PAM} = \frac{1}{T_f}\iint_{-\infty}^{+\infty}\left[w_{rec}(t)w_{rec}(t-s)\right]^2 ds.$

The conditional BER on the instantaneous SNR as (a special case where the L channels are identically distributed with the same average) is: $P_e(\gamma_l) = Q\sqrt{2SINR}$.

Then,

$$P_e \approx \frac{1}{2}\left(1+\frac{\frac{1}{m}}{\frac{1}{\overline{\gamma}}+\frac{N_h-1}{N_s}L\sigma_{PAM}}\right)^{-mL},$$

$$\overline{\gamma} = \frac{1}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}}-1\right)}-\frac{N_h-1}{N_s}L\sigma_{PAM}},$$

$$P_t T_{ac} = \frac{\frac{N_0 G_d N_s N_h N}{\Omega}}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}}-1\right)}-\frac{N_h-1}{N_s}L\sigma_{PAM}}.$$

The total energy of a TH-PAM system in a Nakagami-m channel with a path-loss is:

$$E_{TH\text{-}PAM} = (1+\alpha)\frac{\frac{aN_0 G_d N_s N_h}{\Omega}}{\frac{1}{m\left(2P_e^{\frac{-1}{mL}}-1\right)}-\frac{\frac{N_h}{2}-1}{N_s}L\sigma_{PAM}} + \frac{(P_c-P_{pa})T_{ac}}{N}.$$

4.5. TH-PPM

In this case the same scheme as the TH-PAM case is used, but for modulation $P_e(\gamma_l) = Q\sqrt{SINR}$. The total energy consumption of a TH-PPM system in a Nakagami-m channel with a path-loss is:

$$E_{TH\text{-}PPM} = (1+\alpha)\frac{\frac{aN_0 G_d N_s N_h}{\Omega}}{\frac{1}{2m\left(2P_e^{\frac{-1}{mL}}-1\right)}-\frac{\frac{N_h}{2}-1}{N_s}L\sigma_{PPM}} + \frac{(P_c-P_{pa})T_{ac}}{N}.$$

where

$$\sigma_{PPM} = \frac{1}{T_f}\iint_{\infty}^{+\infty}\left[w_{rec}(t)\left(w_{rec}(t-s)-w_{rec}(t-s-\delta)\right)\right]^2 ds.$$

5. Simulation Results

In this section, the simulation results of the total energy needed to transmit one bit using the different access techniques. To compare the energy efficiency of the previously analyzed multi-user techniques, the different sets of parameters are explored. It is assumed that the communication bandwidth has a minimum value $B = 500$ MHz with center at $f_c = 3.46$ GHz situated in the low part of the 3.1–10.6 GHz UWB band. The all the system parameters chosen as being representative of realistic equipment using

the current CMOS technology: $f_c - 3.46$ GHz, $\alpha = 0.78$, $N_0 = -170$ dBm/Hz, $B = 500$ MHz, $N = 10^6$, $P_{pg} =$ 25.2 mW, $P_{LNA} = 7.68$ mW, $P_{mix} = 15$ mW, $P_{pg} = 2.5$ mW, $P_{ADC} = 7.6$ mW, $P_{filt} = P_{filr} = 2.5$ mW, $L = 4$, $P_e = 10^{-3}$, $M_l = 40$ dB, $G_1 = 33.2$ dB, $\Omega = 1$ ([3] and [4]).
All the experiments are performed in an NLOS propagation channel with $m = 0.7$, which is the depth of fading valid for all the following test configurations. The authors successively consider two different simulation scenarios. The first one maintains the same number of users, the second one imposes the same rate.

5.1. Using with Same Number of Users

In Fig. 2, the requested transmission energy DS-UWB with orthogonal (T-OVSF, ZCD) and non-orthogonal (Kasami I) codes and TH-BPSK-PSM described above versus the distance $d = 5 \ldots 50$ m, for $P_e = 10^{-3}$ and $z = 3.5$ is depicted. The purpose of this initial test is to check the compliance of the selected UWB system power transmission regarding the FCC authorized standard.

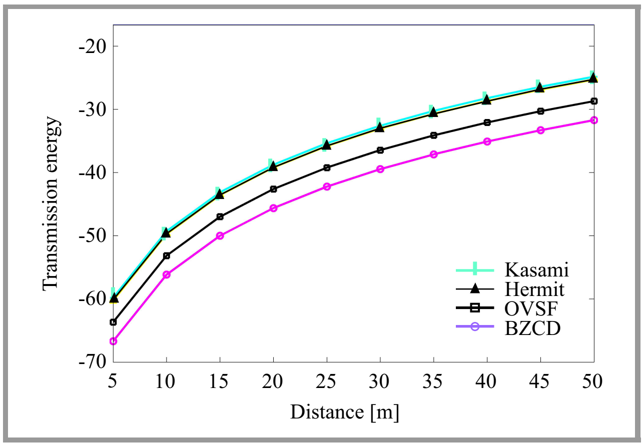

Fig. 2. Transmission energy for different multi-users techniques.

All the techniques studied are compliant with the UWB mask for the whole set of communication ranges. In addition the Kasami technique requires more transmission energy as compared to other techniques. Due to the need for a high number of pulses to handle 16 users, Kasami consumes more energy than that needed for the orthogonal codes and the MHP.
In Fig. 3, the total energy consumption for different multi-user access technique versus distance is presented where in Nakagami-m fading channel and same condition as in Fig. 2.
From the beginning to the end of the, BZCD is the most efficient access technique. It consumes less energy to handle 16 users because it has the advantage of using the least number of pulses compared to the other techniques. While, BZCD codes need 64 pulses to handle 16 users OVSF codes need 128 and the Kasami codes 255. In simulation 8 pulses for the MHP were used, but since the frame duration of MHP to manage 16 users is higher than the frame duration

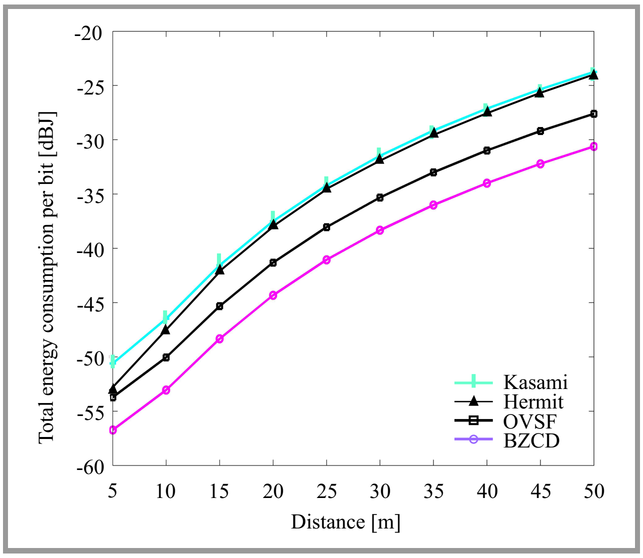

Fig. 3. Total energy for different multi-users techniques using in Nakagami-m fading channel.

of BZCD, MHP technique consumes more than the BZCD one, even with less pulses. The Kasami codes are not very efficient on the whole set of ranges due to the huge number of pulses needed for supporting 16 users. The number of pulses plays a major role in the overall energy consumption since the circuitry required energy and the transmission energy becomes higher and higher with the increase of the number of pulses to be generated.
In Fig. 4, the total energy consumption against the path-loss z is shown using parameters $d = 30$ m, $P_e = 10^{-3}$ and $z = 2.8 \ldots 4.2$ in the Nagakami-m fading channel.

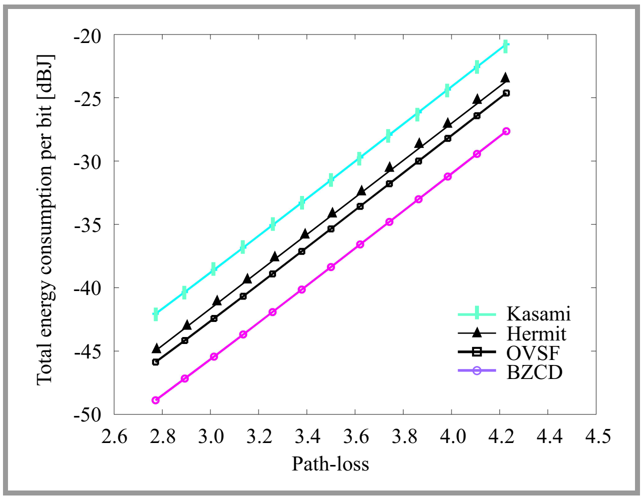

Fig. 4. Total energy for different multi-users techniques vs. path loss z.

Using these settings, the BZCD is the most efficient access technique and that Kasami is the less efficient one. For this particular considered distance and path-loss range, using fewer pulses to transmit the data bits is helpful to achieve an energy efficient system.

5.2. Using the Same Rate

In these experiments, the TH-PPM is compared with other techniques. The latter needs to double the signal processing time, therefore it is suitable to add the power consumption of a microcontroller. It is assumed that 20% of the energy is consumed by the reception circuitries.
In Fig. 5, the transmission energy for four of the multi-user techniques described above versus the distance are depicted, in Nakagami-m fading channel.

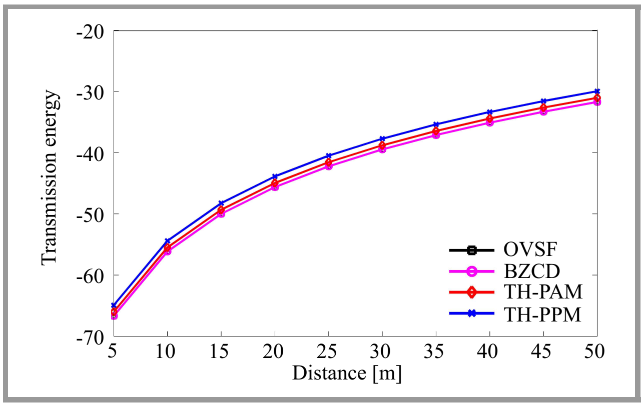

Fig. 5. Transmission energy for different multi-users techniques in Nakagami-m fading channel.

The orthogonal codes request the lowest transmission energy. The highest transmission energy is required by the TH-PPM technique.
In Fig. 6, the total energy consumption for different multi-user access techniques versus the distance is shown using $d = 5 \ldots 50$ m, $P_e - 10^{-3}$ and $z = 3$ in the Nakagami-m channel. To maintain the same rate, $N_c = N_h N_s$ is assumed.

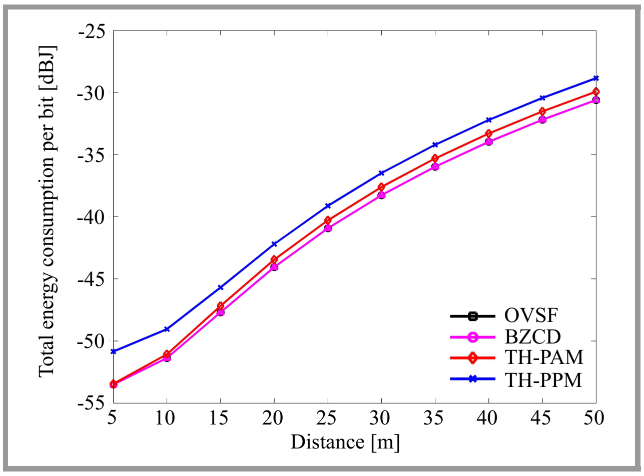

Fig. 6. Total energy for different multi-users techniques vs. distance in Nakagami-m channel.

The simulation results show that T-OVSF and BZCD are the most efficient multi-access techniques from the beginning of the selected communication range up to its end. Despite the use of fewer pulses, TH-PAM and TH-PPM are less efficient than both orthogonal codes. However, TH-PAM is better than TH-PPM energetically speaking. This is due to the robustness of TH-PAM against the multi-user interference. Even if T-OVSF and BZCD consume the same amount of energy for the same number of pulses used, BZCD can handle up to 16 users unlike T-OVSF codes, which are limited to 8 (in this setting). This makes BZCD a better choice. Some tradeoff between the number of users and the energy consumed may be performed if the application demands it.
Figure 7 shows the total energy consumption for different multi-user technique against the path-loss z ($d = 30$ m, $P_e = 10^{-3}$, and $z = 2.8 \ldots 4.2$) in the Nakagami-m channel.

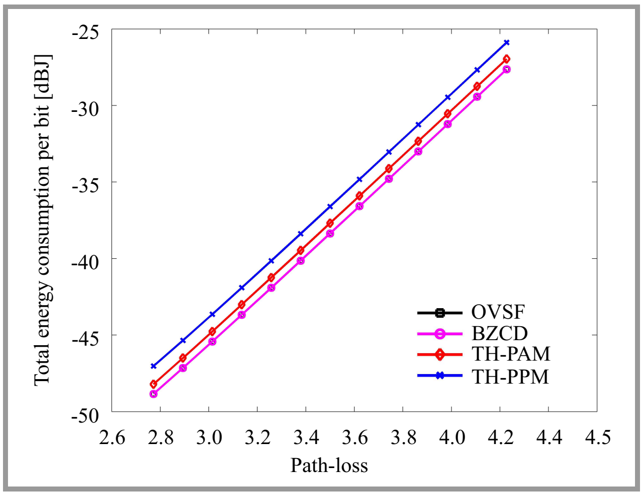

Fig. 7. Total energy for different multi-users techniques vs. path-loss in Nakagami-m channel.

In this considered range, T-OVSF and BZCD are the most efficient techniques over the whole range of path-loss. For the same duration frame, the orthogonal codes are better choice than the time hopping one. This energy efficiency is linked to the influence of the multi-user scenario. When the interference variance increases the total energy consumed increases.

6. Conclusion

In order to develop an energy efficient UWB multi-user, high bit rate, communication system, this paper compared DS-UWB using orthogonal or non-orthogonal codes and different TH-UWB techniques. They were evaluated in Nagakami-m fading propagation channels. In the first part, the different theoretical expressions of the consumed energy were established. Then, in the second part, simulations were run to effectively compare the consumed energy. In the first step, a fixed number of users were considered. We found that the BZCD are more efficient for the range of distances considered and for the whole interval of path-loss coefficient. This first experiment showed that the efficient system is the system using the least number of pulses to transmit the data bit. In the second set of experiments, the transmission rate was fixed. The T-OVSF and BZCD are the less energy consuming for the whole range of distances. Besides, when the distance has a middle value and the path-loss varies, T-OVSF and BZCD remain less energy consuming than the other techniques considered. The second experiment showed that the least efficient technique is the technique having the highest interference variance. To conclude, this energetic model can be further used as a green communication tool to determine the best multi-user techniques regarding energy consumption in a given transmission conditions.

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