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Energy Efficiency Analysis of a TR-UWB System

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Abstract: In wireless communications, where sensors operate on batteries, the energy consumption must be reduced while considering the communication range and data rate requirements. In this context we analyze and compare, in this study, the UWB and TR-UWB system in terms of the total energy consumption. So, for that, we develop an analytical model to estimate the energy consumption of a UWB system using a TR technique. We then compare the consumption of a TR-UWB system and a UWB system in two different propagation environments. We show that the TR-UWB system is more energy efficient than the UWB system in the chosen environments for LOS. However in case of NLOS, TR-UWB is more efficient when we use a bi-symbol modulation for different ranges of distance in both environments.

Keywords: UWB Communication Systems, Energy Consumption, Green Communication, IEEE 802.15.4a Channel, Time Reversal TR

Introduction

The spread of wireless devices in the last years has increased the demand of more networks and higher data-rate speed. This increasing demand comes at the cost of more energy consumption, which has not only increased the expenses of sustaining the wireless networks, but the need for expensive batteries for the devices. This also contributes to increase the percentage of Electromagnetic (EM) radiation in the air. In recent years researchers have tried to develop energy-efficient protocols in order to reduce the energy consumption of wireless networks. The discipline that deals with these issues is called "Green Communication" as explained in Chuan and Anqing (2011). To decrease the level of EM radiation, Time Reversal (TR), presented in Fall *et al*. (2014) and could be a ground breaking technique since one advantage of this technique is the focus of the radiofrequency energy on the intended user. This technique will be described in more detail in the following section 1. In this way, the other users are not polluted by the energy destined to the main user.

Ultra Wideband (UWB) was introduced by Win and Scholtz (1998) and it is a radio technology that offers the ability to create efficient energy and low complexity communication systems at high rate and limited cost. Therefore, we select this radio technology. In addition to this choice, we couple the TR technique with the UWB technology to focus radio energy on the receivers. Many research efforts have been done to discuss the performance of the UWB systems using TR. Tran and Tran-Ha (2013) have shown that TR applied to UWB increases channel capacity and performs better than the traditional UWB system in high noise environment.

Nguyen *et al*. (2006) used a multiple antenna system 4×1 to show that TR has a great potential in simplifying the receiver complexity and enhancing the UWB system performance. Zhou *et al*. (2007) analyzed the performance of the UWB system using multiple antennas. They found that the UWB system with TR can achieve more power gain if we use more antennas at the transmitter and the receiver, while keeping low complexity at the receiver side. Ferrante *et al*. (2013) compared the performance of UWB using TR and

UWB implemented on rake receivers. The results show that TR is better in terms of average SNR. They also show that the TR with multiple antennas has better performance and focusing with respect to the system using one single antenna.

Coupling TR with UWB has proven to give better results in localization than the traditional UWB system. Fall *et al*. (2014) conducted analytical and simulation studies in two different environments in a controlled environment (anechoic chamber with reflectors) and in a tunnel. Considering positioning accuracy, they have found that the UWB system using TR is more precise that the system without TR. Moreover, they have shown that coupling TR and UWB technique provides a position error of less than 10 cm for localization application. Zhang and Qin (2014) proposed a low cost location system based on UWB and this open a door for massive production.

Wang *et al*. (2011) investigate the energy consumption impact of TR on wireless communications specially the CDMA technique and the ability to alleviate the interference also. Using numerical simulations and experimental measurements, the authors show that TR technique can reduce the transmission power consumption on the one hand and alleviate the interference on the other hand. They concluded that TR is a suitable technique for “green communication”.

In the literature, to our knowledge, there are no analytical models for TR-UWB system to quantify the energy consumed according to the parameters of communication such as: Modulation and coding techniques.

In the context of green communication, it is necessary to estimate the energy consumed according to the channel model and the constraint required by the application (data rates, range…).

This paper is a contribution to this research activity. Its aim is to develop an analytical model that computes the total energy consumption of a TR-UWB system in a Nakagami-m channel. Molisch *et al*. (2004) described the UWB IEEE 802.15.4a channel. The authors used the Nakagami-m distribution to model the channel amplitudes.

In this study, total energy consumption means the transmission energy considered in Cui *et al*. (2005) as well as the energy consumed in the circuitries. We present the results of our numerical simulations in which we compare the energy consumption of TR-UWB system with the traditional UWB system in two different environments.

The rest of the paper is organized as follows. We discuss the TR technique and provide the channel description in section 1. In section 2, we present the energetic model. In section 3, we analyze the energy efficiency of the UWB system applying TR and the energy efficiency of the traditional UWB. We present the results of our numerical simulations in sections 4. Conclusion and perspectives are finally drawn.

Time Reversal and Channel Description

A conventional Time Reversal (TR) communication technique consists in pre-filtering the signal by the reversed complex conjugate of the channel Impulse Response (IR). Then, the output signal after the filtering is convolved with the channel IR. Hence, we can write the received signal of a Single Input and Single Output (SISO) system using TR as follow:

$$y(t) = s(t) * h(-t)^H * h(t) + n(t)$$

To simplify the expression we can write:

$$y(t) = s(t) * h^{eq}(t) + n(t) \quad (1)$$

where*, H and $h^{eq}(t)$ respectively denote convolution, complex conjugate and the autocorrelation of the channel IR.

In Fig. 1, the signal at the output of the transmitter (a) is the inverse of the channel IR $h(-t)$, between the transmitter (a) and the receiver (b) we can see the channel IR $h(t)$. The signal at the input of the receiver (b) is the convolution of the two signals $h_{eq}(-t)$. The transmitter’s and the receiver’s components are detailed in section 3.

Due to the multi-path propagation the receiver receives the same transmitted signal multiple times with different attenuations and delays. The received signal can be written as the sum of all the signals generated by the different paths. Thus, we can model the UWB channel as the sum of L taps and L tap delays Equation 2:

$$h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l) \quad (2)$$

where, α_l is the l-th amplitude τ_l and the l-th delay associated with the l-th tap. $\delta(t)$ is a Dirac function.

We can compute the value of the $h^{eq}(t)$ using the expression 2 as:

$$\begin{aligned} h^{eq}(t) &= \left(\sum_{l=1}^{L} \alpha_l \delta(t - \tau_l)\right) * \left(\sum_{l=1}^{L} \alpha_l \delta(-t - \tau_l)\right) \\ &= \sum_{l=1}^{L} \alpha_l^2 \delta(t - \tau_l) * \delta(-t - \tau_l) \\ &+ \sum_{l=1}^{L} \sum_{k=1, k \neq l}^{L} \alpha_l \alpha_k (t - \tau_l) * \delta(-t - \tau_k) \end{aligned}$$

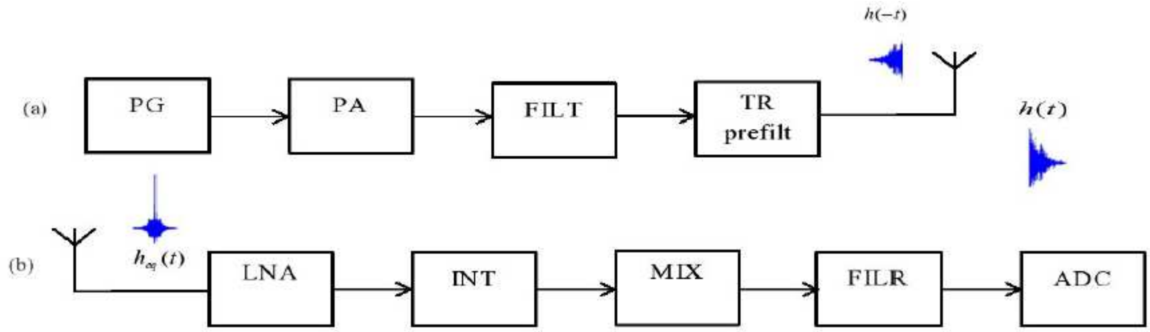

Fig. 1. Time reversal principle: (a) transmitter architecture, (b) receveir architecture

In reception, we use a matcher filter synchronized on the peak of the autocorrelation of the IR. This will enhance the spatial and time focus of the TR system. So, the value of the $h^{eq}(t)$ at the peak is Equation 3:

$$h\max = \sum_{l=1}^{L} \alpha_l^2 \quad (3)$$

To normalize the transmission power of our system we multiply the signal by a scaling factor $A = 1 \Big/ \sqrt{\sum_{l=1}^{L} \alpha_l^2}$.

So the Equation 1 becomes Equation 4:

$$y(t) = As(t) * h^{eq}(t) + n(t) \quad (4)$$

For the distribution of the amplitudes α_l, we shall consider a Nakagami-m distribution as published in the Molisch *et al*. (2004) and we shall use some specific parameters all along with the path loss values described in Molisch *et al*. (2004) for different environments.

The gain of the channel for a distance d can be written as $G_d = P_t/P_s = 2PL_0(d/d_0)^n(f/f_c)^{2(k+1)}$, where P_s and P_t are the received power (energy per symbol) and the transmitted power respectively, d is the distance between the transmitter and the receiver, G_0 is the channel gain for d_0 = 1 m, n is the path-loss component, k is the frequency dependence of the path-loss. The values of these different parameters are given in Molisch *et al*. (2004) for a set of specific environments.

Adding the channel gain to the received signal, we rewrite the Equation 1 in the form Equation 6:

$$y(t) = \frac{A}{\sqrt{G_d}} s(t) * h^{eq}(t) + n(t) \quad (5)$$

Energetic Model

In order to study the energy consumption of a wireless communication system, we exhaustively consider the electronic components used in the telecommunication chain.

Sending a sequence of N bits necessitates an amount of time noted T. 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}. In this case, all the components are working and 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 necessary components are active and consuming power
- Transient mode: This corresponds to the transition mode between the sleep mode and the active mode. The time spent by the transceiver in this transient mode is noted T_{tr}

Thus, *T* can be written according to Equation 6:

$$T = T_{sl} + T_{tr} + T_{ac} \quad (6)$$

In Cui *et al*. (2005), 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 synthesizer, which is energy consuming when the transition takes place. In our case, for the UWB Impulse Radio technique, we do not use a synthesizer. So, we do not take into account this transient time. Therefore, the energy needed to transmit N bits is given by Equation 7:

$$E = P_{sl}T_{sl} + P_{ac}T_{ac} \quad (7)$$

P_{ac} and P_{sl} represent the power consumption values 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 Pct. In a further section, we shall detail the composition of these powers because the associated hardware components may change, according to the type of the transmission techniques. In the transmission part, we also use a Power Amplifier noted PA. Its power consumption is linked to the transmission power by: $P_{amp} = aP_t$, where a = ξ/η-1, with ξ the average of peak to ratio and η the drain efficiency of the PA. These variables depend on the class of the amplifier and of 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, we also assume that $P_{sl} = 0$. 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 Equation 8:

$$ET = \frac{\lfloor (1+a)P_t + (P_c - P_{amp}) \rfloor T_{ac}}{N} \quad (8)$$

UWB and TR-UWB Energy Efficiency Analysis

UWB System

In this section we describe a UWB system using a Pulse- Amplitude Modulation (PAM) and a rake receiver with a matched filter associated to each of its different branches. So, the expression 9 depicts a typical UWB signal Equation 9:

$$s(t) = \sqrt{\frac{P_t}{N_s}} \sum_{j=-\infty}^{j=+\infty} A_{b_{\lfloor j/N_s \rfloor}} \, p(t - jT_f) \quad (9)$$

where, $b_{\lfloor j/N_s \rfloor}$ is the transmitted symbol, $A_{b_{\lfloor j/N_s \rfloor}} \sqrt{\frac{P_t}{N_s}}$ is one of the possible amplitude with $A_{b_{\lfloor j/N_s \rfloor}} = 2b_{\lfloor j/N_s \rfloor} - 1 - M$ and is the number of symbols.

T_f is the time duration of a frame and the duration of a symbol is $T_s = N_s T_f$ where N_s is the number of pulses used to transmit a symbol.

The system bandwidth is $B = 1/T_p$ where T_p is the width of a pulse. We consider the duty cycle $\beta = T_f/T_p$ and we know that the duration of a frame is at least one hundred times the pulse width in UWB, so β >100 to limit jamming. We also assume β >> M. T_f = β/B and, by taking $N_s = 1$, we also have Ts = β/B. We can write T_{ac} = N $T_s/\log_2(M)$. We conclude that T_{ac} = N β/Blog2(M).

The transmitter power consumption is computed as the sum of the power consumption of a pulse generator noted P_{pg}, a P_{amp} and a filter noted P_{filt}:

$$P_{ct} = P_{pg} + P_{amp} + P_{filt}$$

For reception, we choose a partial rake receiver using the maximum ratio combiner technique. Hence, the power consumption of the receiver circuitry is the sum of the power consumption of the low power amplifier (LNA) noted P_{LNA}, an integrator Pint, a mixer P_{mix}, a filter (P_{filr}) and an analog to digital converter (PADC):

$$P_{cr} = P_{LNA} + L_R\left(P_{mix} + P_{\text{int}}\right) + P_{filr} + P_{ADC}$$

With L_R denotes the number of branches of the rake receiver.

The instantaneous SNR of our system can be written as $\gamma_l = \frac{\alpha_l^2 P_t}{G_d N_0 B}$ and the average instantaneous SNR is $\bar{\gamma}_l = \frac{\Omega_l P_t}{G_d N_0 B}$ with $\Omega_l = E\left[\alpha_l^2\right]$ is the Power Delay Profile (PDP) and can be written as in Nguyen (2008) Equation 10:

$$\Omega_l = \exp\left(\frac{-(l-1)\Delta\tau}{\bar{\sigma}_\tau}\right) \quad (10)$$

where, $\Delta\tau$ is the time duration between two consecutive taps and $\bar{\sigma}_\tau$ represents the RMS delay spread.

The symbol error rate conditioned on the instantaneous SER in Proakis (2001) is:

$$P_M(\gamma_l) = \frac{2(M-1)}{M} Q\left(\frac{6\sum_{l=1}^{L_R}\gamma_l}{M^2-1}\right)$$

Thus, using the equations in Proakis (2001) and Simon and Alouini (1998), the average Symbol Error Rate (SER) of M-ary PAM in Nakagami-m channel can be upper bounded by Equation 11:

$$\begin{aligned} P_M &= \iint \dots \int_0^{+\infty} P_M(\gamma_l) f_\gamma(\gamma_l) d\gamma_1 \dots d\gamma_{L_R} \\ &\le \frac{M-1}{M} \prod_{l=1}^{L_R} I(\bar{\gamma}_l) \end{aligned} \quad (11)$$

With:

$$I\left(\overline{\gamma_l}\right)=\frac{M-1}{M}\left(1+\frac{3\overline{\gamma_l}}{m\left(M^2-1\right)}\right)^{-m}$$

Where:
L_R = The rake fingers and
m = The Nakagami-m shape parameter

For the special case where the L_R channels are identically distributed with the same average SNR $\overline{\gamma_l}$ and $\Omega_l = \Omega$, the expression 11 will be simply written as Equation 12:

$$P_M=\frac{M-1}{M}\left(1+\frac{3\overline{\gamma_l}}{m\left(M^2-1\right)}\right)^{-mL_R} \quad (12)$$

So, the average SNR can be expressed as:

$$\overline{\gamma_l}=m\left(\frac{M^2-1}{3}\right)\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_R}-1\right)$$

We deduce that:

$$P_t\,T_s=m\left(\frac{M^2-1}{3}\right)\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_R}-1\right)\frac{N_0G_d}{\Omega}$$

Then:

$$P_t\,T_{ac}=m\left(\frac{M^2-1}{3}\right)\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_R}-1\right)\frac{N_0G_dN}{\Omega\log_2\left(M\right)} \quad (13)$$

Finally, by replacing Equation 13 in Equation 8, we obtain Equation 14 proposing the total energy consumed by a UWB transceiver operating in a Nakagami-m channel with path-loss, transmitting one symbol:

$$E_{UWB}=\left(1+a\right)m\left(\frac{M^2-1}{3}\right)\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_R}-1\right)\frac{N_0G_dN}{\Omega\log_2\left(M\right)}+\frac{\left(P_c-P_{amp}\right)T_{ac}}{N} \quad (14)$$

TR-UWB System

For the TR-UWB system, we shall use the same modulation and system parameters as defined for the UWB system.

The TR pre-filtering stage requires another filter block to convolve the UWB signal, we shall assume that the pre-filter consume the same energy as the filter. Then, the TR system transmitter is computed as:

$$P_{ct}=P_{pg}+P_{amp}+P_{filt}+P_{TR}$$

where, $P_{TR} = L_{TR}\Omega P_t$, this value is an estimation to the power consumed by transmitter using a TR technique. This value is the product of the average amplitude of all the paths used to implement TR and the transmission power.

For reception, we consider a matched filter synchronized on the TR correlation peak. Thus, the total power consumption is the sum of an LNA noted PLNA, an integrator P_{int}, a mixer P_{mix}, a filter (P_{filt}) and an ADC (P_{ADC}):

$$P_{ct}=P_{LNA}+P_{mix}+P_{\text{int}}+P_{filt}+P_{ADC}$$

The symbol error rate conditioned on the instantaneous SER is:

$$P_M\left(\gamma_l\right)=\frac{2\left(M-1\right)}{M}Q\left(\sqrt{\frac{6\sum_{l=1}^{L_{TR}}\gamma_l}{M^2-1}}\right)$$

Thus, using the equations in Proakis (2001) and Simon and Alouini (1998), the Average Symbol Error rate (SER) of M-ary PAM in Nakagami-m channel can be upper bounded by:

$$\begin{aligned}P_M&=\iint\dots\int_0^{+\infty}P_M\left(\gamma_l\right)f_\gamma\left(\gamma_l\right)d\gamma_1\dots d\gamma_{L_{TR}}\\&\le\frac{M-1}{M}\prod_{l=1}^{L_{TR}}I\left(\overline{\gamma_l}\right)\end{aligned} \quad (15)$$

With:

$$I\left(\overline{\gamma_l}\right)=\frac{M-1}{M}\left(1+\frac{3\overline{\gamma_l}}{m\left(M^2-1\right)}\right)^{-m}$$

At the reception side we use a window of L_{TR} taps and we assume that the channels are identically istributed with the same average SNR $\overline{\gamma_l}$ and $\Omega_l = \Omega$, the expression 15 will be simply written as:

$$P_M=\frac{M-1}{M}\left(1+\frac{3\overline{\gamma_l}}{m\left(M^2-1\right)}\right)^{-mL_{TR}} \quad (16)$$

So, the average SNR can be expressed as:

$$\overline{\gamma_l} = m\left(\frac{M^2-1}{3}\right)\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_{TR}}-1\right)$$

We deduce that:

$$P_t\,T_s = m\left(\frac{M^2-1}{3}\right)\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_{TR}}-1\right)\frac{N_0G_d}{\Omega}$$

Then:

$$P_t\,T_{ac} = m\left(\frac{M^2-1}{3}\right)\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_{TR}}-1\right)\frac{N_0G_dN}{\Omega\log_2(M)} \quad (17)$$

Finally, by replacing Equation 17 in Equation 8, we obtain Equation 18 proposing the total energy consumed by a TR-UWB transceiver operating in a Nakagami-m channel with path-loss, transmitting one symbol:

$$\begin{aligned} &E_{TR-UWB} \\ &= \left(1+a+L_{TR}\Omega\right)m\left(\frac{M^2-1}{3}\right) \\ &\left(\left(\frac{MP_M}{M-1}\right)^{-1/mL_{TR}}-1\right)\frac{N_0G_dN}{\Omega\log_2(M)} \\ &+\frac{\left(P_c-P_{amp}\right)T_{ac}}{N}\end{aligned} \quad (18)$$

Simulation Results

In this section we compare the energy consumption of the conventional UWB system and the TR-UWB system in order to find out the most efficient system to use. For these experiments we use relevant IEEE 802.15.4a standard parameters and illustrate the energy efficiency of the systems in three different environments for the Line Of Sight (LOS) case and Non-Line Of Sight (NLOS) case. The powers of the circuitry blocs and some other common parameters for all the environments are presented in the Table 1.

Residential Environment

We assume that the number of taps L = 100 is the same for the LOS case and the NLOS case, the channel parameters and path-loss are presented in Table 2.

In Fig. 2 and 3, we depict the total energy consumption of the UWB system and TR-UWB system versus the number of symbols, where $M \in \{2, 4, 8, 16, 32, 64\}$, $P_M = 10^{-3}$, d = 15 m, L_{TR} = 4 and L_R = 4 for LOS case and NLOS case respectively.

We obtain that the TR-UWB system is more efficient than the UWB system alone for all the variations of M, except for M = 64 in the LOS case. However, the traditional UWB system consumes less energy in the NLOS case for all constellations. We notice that the energy efficiency is different for the two cases. That can be explained by the high value of the transmission energy in the NLOS case. The energy of the TR-UWB transmitter is more sensitive to the transmission energy increase than the normal UWB one it is the reason why TR-UWB is less efficient (for NLOS). In the case of LOS, the most efficient constellation values for TR-UWB and UWB are M = 16 and M = 32 respectively. But the values are different in the case of NLOS, both systems consume the least amount of energy when M = 2. The optimal constellation is different for the two cases. The transmission energy is lower in the LOS case, hence an increase of the data rate decreases the total energy consumed until a certain value of M (32 for TR-UWB and 64 for UWB) where the total energy starts to increase.

Table 1. System parameters

f_c = 5 GHz	f = 3.85 GHz	B = 1.5 GHz
N = 106	P_{pg} = 25.2 mW	P_{LNA} = 7.68 mW
P_{mix} = 15 mW	P_{int} = 2.5 mW	P_{ADC} = 7.6 mW
P_{filt} = 2.5 mW	$P_{pre\text{-}filt}$ = 2.5 mW	P_{filr} = 2.5 mW
P_M = 10-3	a = 0.78	N_0 = -170 dBm/Hz
$\Delta\tau$ = 0.7	β = 500	

Table 2. Residential environment parameters

LOS	NLOS
n = 1.79	n = 4.89
k = 1.24	k = 1.85
PL_0 = 43.9 dB	PL_0 = 48.7 dB
m = 0.67 dB	m = 0.69 dB
Ω = 0.93	Ω = 0.94
σ_τ = 14	σ_τ = 18
Distance range 5-17 m, Frequency range 3-6 GHz	Distance range 5-20 m, Frequency range 3-6 GHz

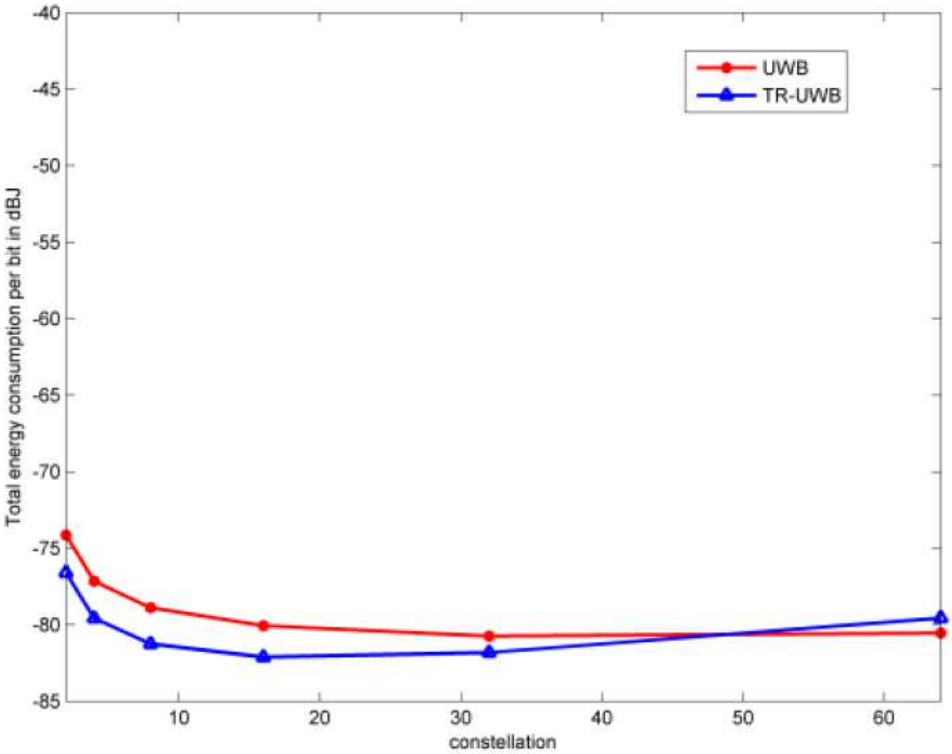

Fig. 2. Total energy consumption for one symbol for UWB and TR-UWB with M∈{2, 4, 8, 16, 32, 64}, $P_M = 10^{-3}$, d = 10 m

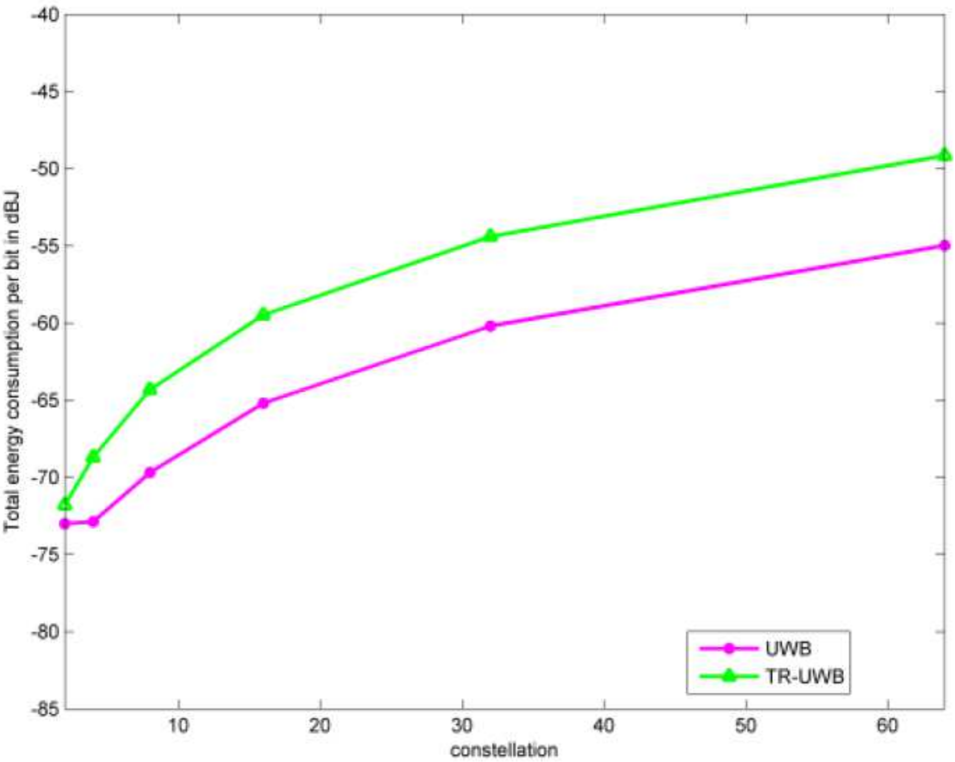

Fig. 3. Total energy consumption for one symbol for UWB and TR-UWB with M∈{2, 4, 8, 16, 32, 64}, $P_M = 10^{-3}$, d = 10 m

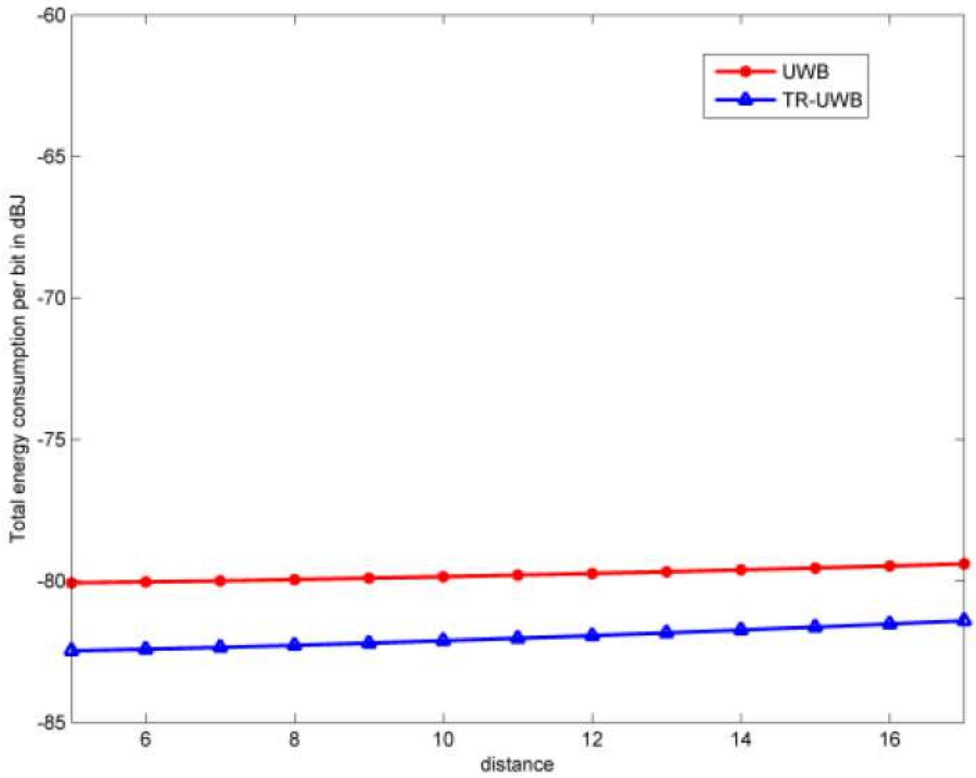

Fig. 4. Total energy consumption for one symbol for UWB and TR-UWB with d = [5 17 m], PM = 10^{-3}

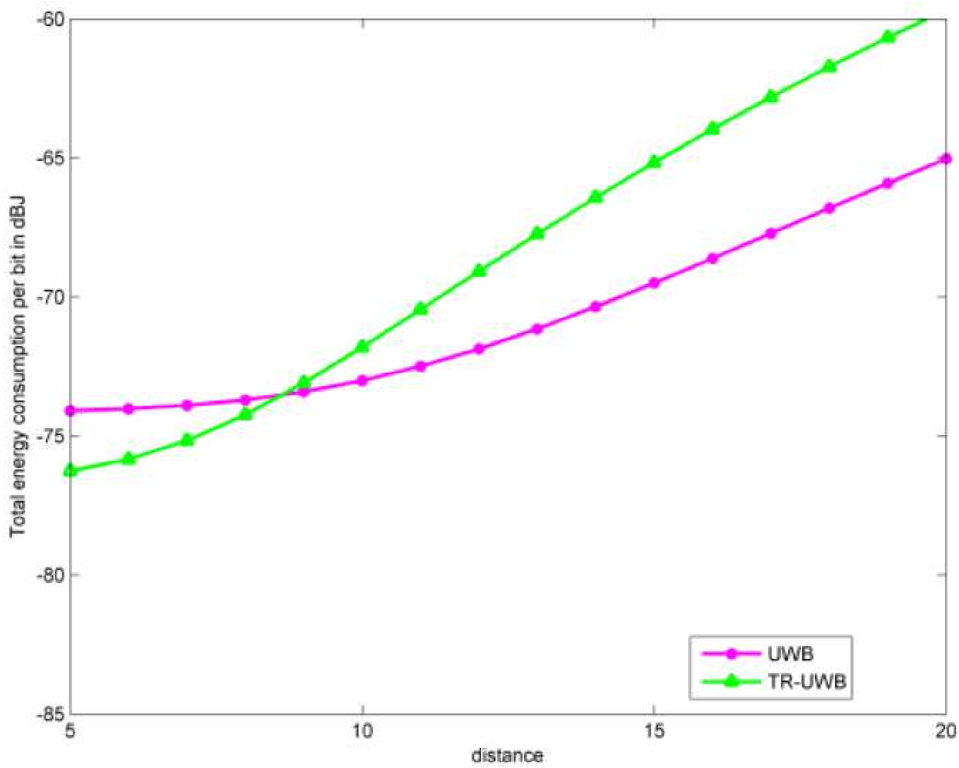

Fig. 5. Total energy consumption for one symbol for UWB and TR-UWB with d = [5 20 m], $P_M = 10^{-3}$

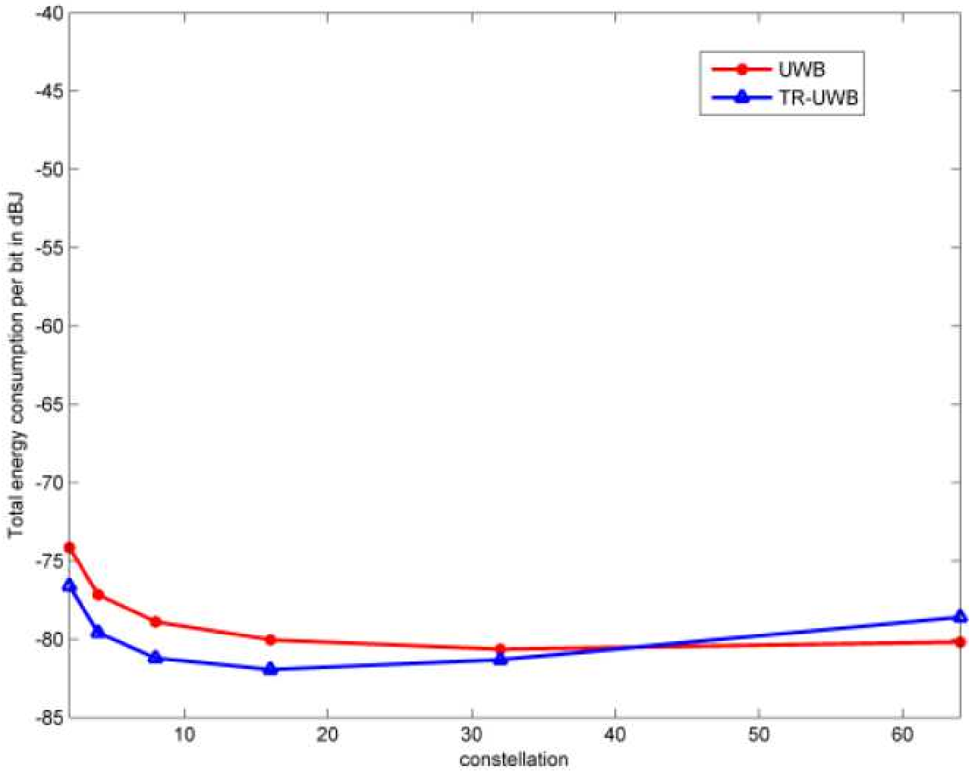

Fig. 6. Total energy consumption for one symbol for UWB and TR-UWB with M∈{2, 4, 8, 16, 32, 64}, $P_M = 10^{-3}$, d = 10 m

In Fig. 4 and 5, we represent the total energy consumption of the UWB system and TR-UWB system versus the distance between the transmitter and the receiver, where d = [5 17] and d = [5 20] for LOS case and NLOS case respectively. $P_M = 10^{-3}$, d = 10 m, L_{TR} = 4 and L_R = 4 for both cases.

For the LOS case results presented in Fig. 4, the TR-UWB system is less energy consuming as compared to the UWB system. But for the NLOS case, we notice a change of energy efficiency starting from d = 9 m where the traditional UWB becomes less energy consuming than the TR-UWB. At d = 9 m, the transmitter consumption dominates the transmission energy and explains why this change in efficiency is occurring. We used different communication conditions (varying the number of symbols at a constant communication distance and the other way around) in this section. We showed that the TR-UWB system is less energy consuming than the traditional UWB system in a residential environment for LOS (except when M = 64). However for the NLOS case, TR-UWB is more efficient than UWB alone when M = 2 and the communication range is low (between 5 and 8 m). So, TR-UWB could be a promising technique to be implemented in energy aware wireless devices.

Outdoor Environment

We assume that the number of taps L = 100 is the same for the LOS case and the NLOS. The channel parameters and path-loss are presented in Table 3.

In Fig. 6 and Fig. 7, we depict the total energy consumption for the TR-UWB and the UWB systems.

We consider a variation of the number of symbols M {2, 4, 8, 16, 32, 64}, where $P_M = 10^{-3}$, d = 10 m, L_{TR} = 4 and L_R = 4 for LOS case and NLOS case respectively.

We obtain that the TR-UWB system is more efficient in term of energy consumption, in the LOS case, for all M except M = 64.

Unlike the latter, in the NLOS case, UWB is more efficient than TR-UWB for all constellations. While for the LOS case the TR-UWB and UWB systems' most efficient constellations are obtained with M =16 and M = 32 respectively, for NLOS case both systems are less consuming when M = 2.

Table 3. Outdoor environment parameters

LOS	NLOS
n = 1.76 dB	n = 2.5 dB
k = 0.12 dB	k = 0.13 dB
PL_0 = 45.6 dB	PL_0 = 73 dB
m = 0.77 dB	m = 0.55 dB
Ω = 0.99	Ω = 0.99
$\overline{\sigma_\tau}$ = 82	$\overline{\sigma_\tau}$ = 90

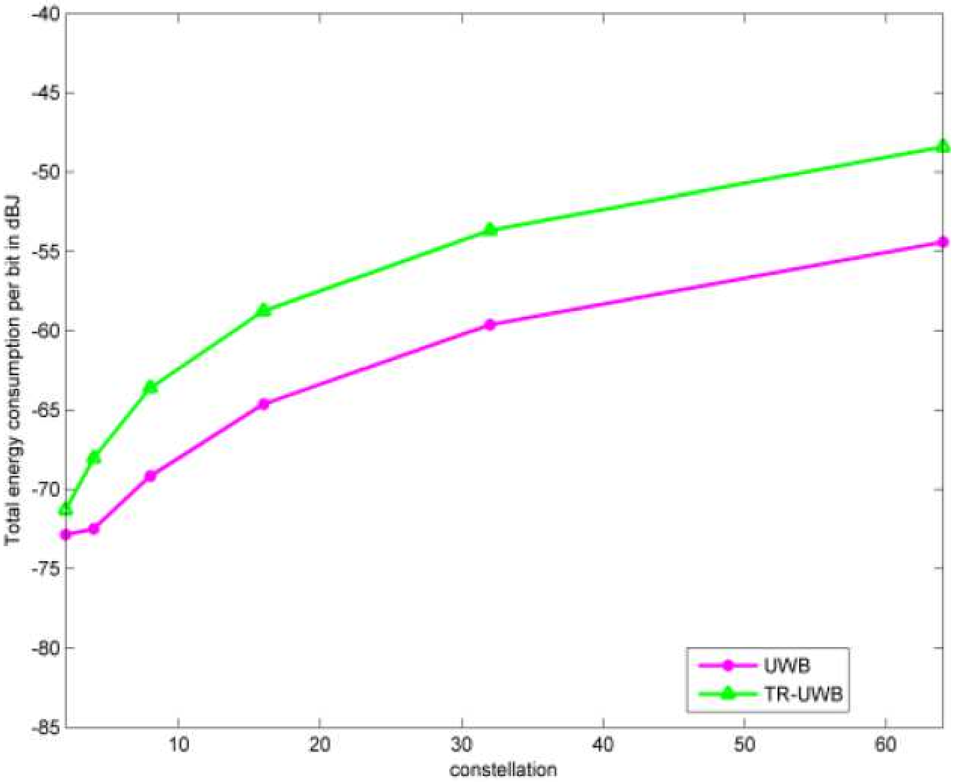

Fig. 7. Total energy consumption for one symbol for UWB and TR-UWB with M∈{2, 4, 8, 16, 32, 64}, $P_M = 10^{-3}$, d = 10 m

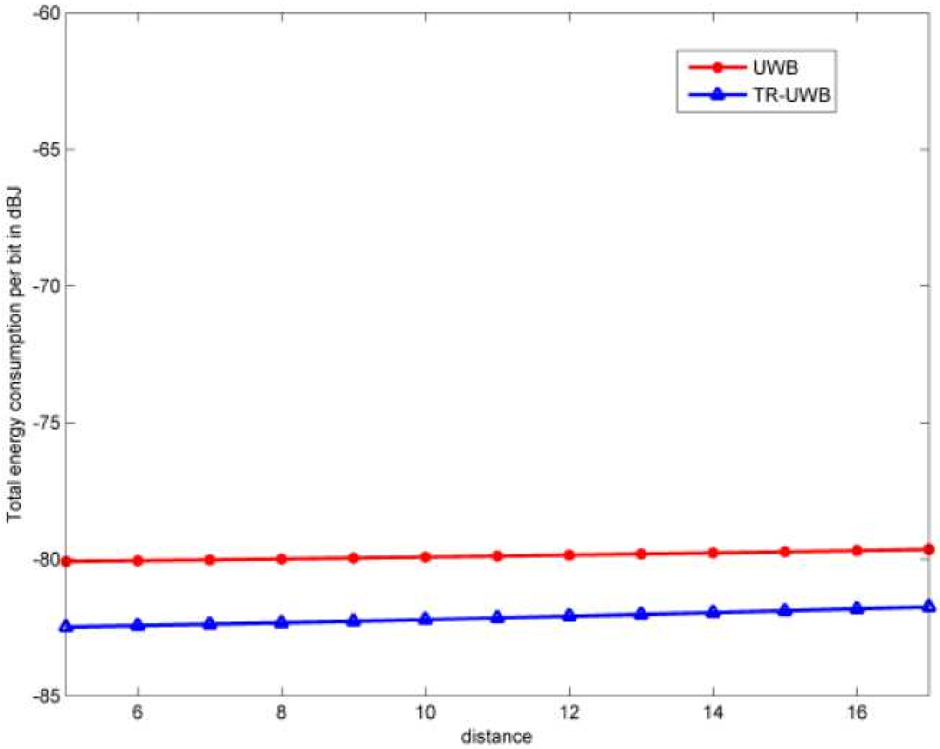

Fig. 8. Total energy consumption for one symbol for UWB and TR-UWB with d = [5 17 m], $P_M = 10^{-3}$

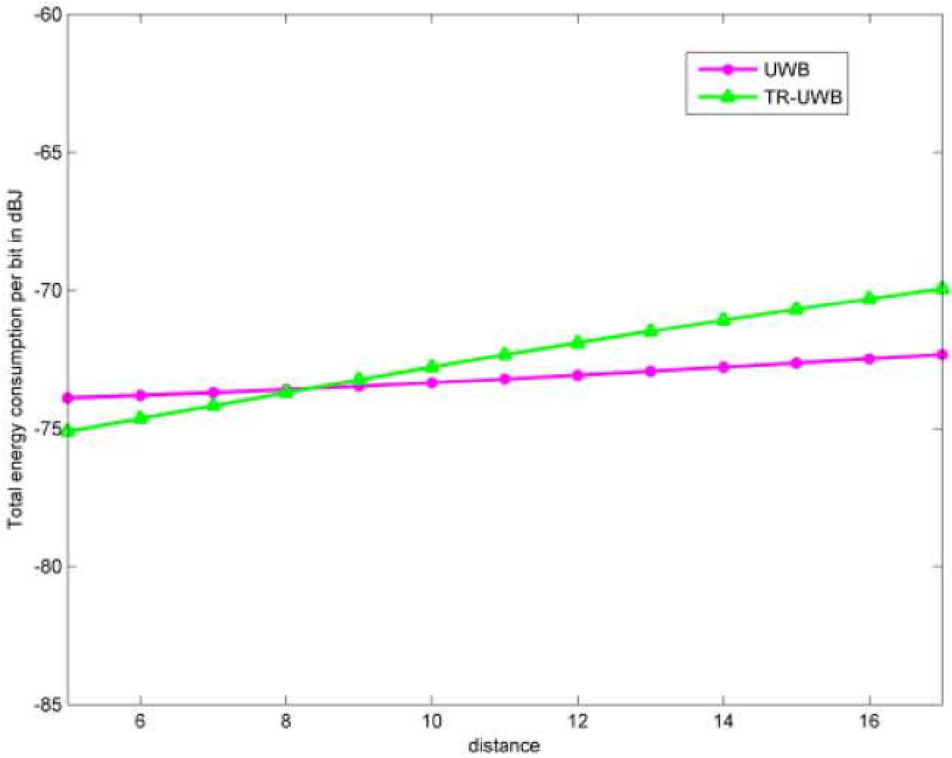

Fig. 9. Total energy consumption for one symbol for UWB and TR-UWB with d = [5 17 m], $P_M = 10^{-3}$

In Fig. 8 and 9, we represent the total energy consumption of the TR-UWB system and UWB system versus a range of distance d = [5 17] where $P_M = 10^{-3}$, d = 10 m, $L_{TR} = 4$ and $L_R = 4$ for LOS case and NLOS case respectively.

As in the previous experiments, we find that the TR-UWB system is more efficient than the UWB system for the whole distance range in the LOS case and for d = [5 8 m] in the NLOS case.

Similar to the results obtained for the residential environment, the TR-UWB system in the outdoor environment is a good choice for the wireless devices with battery constraint. The experiments showed that this system consumes less than the UWB system for different communication conditions in this specific outdoor scenario. Then, TR-UWB can be adopted since it consumes less energy than the conventional system.

Conclusion

In this study we introduced an analytical model capable of computing the total energy consumption of a TR-UWB and UWB system in a Nakagami-m channel. We illustrated the numerical comparison of a UWB system and a UWB system applying TR technique. These simulations were performed in two different environments, a residential environment and an outdoor environment. We started by computing the total energy consumption of both systems in a residential environment varying the number of symbols to find the optimal constellation for every system. Thus, after getting the optimal constellation we represented the consumption of the systems versus a range of distance. The simulations in the residential environment showed that TR-UWB is less energy consuming than UWB for all chosen constellation except M = 64 and for M = 2 where d = [5 9 m] in the NLOS case. We repeated the same steps for the outdoor environment and the results were almost identical to the previous environment. Hence, TR is a promising technique for energy-aware devices or devices with an embedded battery. Therefore, TR is indeed an adequate technique for green communication, since its focusing capacity can not only help in reducing the energy consumption but also, by focusing energy to an intended receiver reduces the polluting signals received by the unintended receivers. The energetic model developed in this study can be used to analyze the energy efficiency of TR-UWB system that uses other modulations just by changing the instantaneous SER which is specific to every modulation.

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Author's Contributions

Adil El Abboubi: Results analysis, running experiments, writing the paper.

Fouzia Elbahhar: Energetic model, revising and editing.

Marc Heddebaut: Channel characteristics analysis, revising and editing.

Raja Elassali: Circuitries consumption data collection.

Yassin Elhillali: Time reversal approach.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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