Self-Reference Ultra-Wideband Systems

Aimilia P. Doukeli, Athanasios S. Lioumpas, Student Member, IEEE,
George K. Karagiannidis, Senior Member, IEEE and Panayiotis V. Frangos

Abstract

In practical Ultra-Wideband (UWB) systems, Rake receivers are not able to fully take advantage of all resolvable paths, because of the required computational and power resources. On the other hand, Transmitted Reference (TR) schemes are simple, robust structures with low power consumption and they do not require channel estimation, but they sustain a 3dB energy/rate loss, as each symbol requires the transmission of two pulses. Alternatively, the Differential TR (DTR) scheme offers 3dB performance gain compared to conventional TR structures and double data rates since the previously transmitted data pulse is used as a reference. In this paper we introduce a less complex, energy-efficient TR scheme, called Self Reference (SR) UWB system, which uses as reference an elaborated replica of the received signal. It is shown that the SR scheme outperforms the DTR one in terms of error performance and achieves double data-rate compared to conventional TR schemes.

Index Terms

Differential Transmitted Reference UWB, fading channel, Self Reference UWB, Transmitted Reference UWB, UWB.

Aimilia P. Doukeli and Panayiotis V. Frangos are with the Department of Electrical and Computer Engineering, National Technical University of Athens, 15700 Athens, Greece (e-mail: {doukeli@mail.ntua.gr ,pfrangos@central.ntua.gr }).
A. S. Lioumpas and G. K. Karagiannidis are with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece (e-mail: {alioumpa;geokarag}@auth.gr).
I. INTRODUCTION

Since 2002, Ultra-Wideband (UWB) systems have received special research interest as a promising technology for high-speed, high-precision, strong penetration short-range wireless communication applications with the ability to overlay existing narrowband systems [1]. Their basic characteristic is the transmission of ultra-short pulses of low-power that occupy a large bandwidth, resulting in high resolvability of multipath components (MPCs) and exploitation of multipath diversity [2] that make UWB a viable candidate for communications in harsh reference scenarios, such as industrial/factory indoor and forest/sub-urban outdoor environments.

In order to fully take advantage of all resolvable MPCs, coherent receivers named as Rake receivers, were proposed [3]. The optimum diversity combining scheme, in terms of performance, is the all-Rake (ARake) receiver which combines all resolvable paths that are often more than 100 [1] in typical UWB scenarios. However, the number of MPCs that can be utilized in a typical Rake combiner is limited by power consumption constraints, complexity considerations, and the availability of channel estimations, leading in discarding a large number of them and consequently in significant performance degradation. Hence the ARake receiver serves only as a benchmark and provides a bound on the performance that is achievable by other suboptimal combining schemes. A Rake receiver that overcomes the aforementioned obstacles at the cost of the performance is the Selective Rake (SRake) receiver which combines a subset of the available resolvable MPCs and specifically the instantaneously strongest $L_b$ paths [4]-[6]. However, SRake receiver still requires full estimation of the channel coefficients that may not always be available. Recently, Partial Rake (PRake) receiver was proposed in [7], which combines only the first arriving $L_p$ paths out of the available resolvable MPCs, and therefore requires accurate synchronization and not full channel estimation at the expense of the performance gain.

In order to eliminate channel estimation, a simple non-coherent scheme for UWB systems was proposed in 2002 by Hoctor and Tomlinson [8], named as Transmitted Reference (TR), which was able to capture the energy of all multipath components. An unmodulated reference pulse is transmitted prior to each data-modulated pulse within the coherence time of the channel in order for the two pulses to experience the same channel condition. An autocorrelation receiver is applied and the received reference signal is used as a template to demodulate the data symbol. Hence, each data pulse in the TR scheme is represented by two pulses, the reference and the signal one, leading in low data rate systems (single reference TR schemes have been proposed where one pilot symbol is used for several data symbols [9]). Moreover, TR systems experience 3dB loss in signal-to-noise ratio (SNR), because of the usage of a noisy template [10].
Another drawback of the TR structure is that the delay line, that must be implemented for the needs of the TR, interrupts the synchronization at the reception of IR signals. Fine synchronization in the sub-nanosecond range for UWB systems is the key parameter in the reception of IR signals, since it is a prerequisite for signal correlation, energy capture, delay estimation, location and positioning applications and data demodulation. Additionally, the delay line adds extra power consumption which is important for mobile and portable systems where UWB are focused.

A simple TR modification scheme was presented in [14], named as Differential TR scheme (DTR), in order to double the data rate, reduce the inter-symbol interference (ISI) and obtain a 3 dB gain in performance. In DTR the data are differentially modulated using the previously sent pulse, instead of transmitting an extra reference pulse. However, the performance in terms of the average bit error probability (ABEP) of DTR suffers from the noisy reference and from the assumption that the coherence time of the channel equals the duration of two symbols. Moreover, the implementation of the delay line causes synchronization issues which are critical for the performance of the system.

In this paper, we introduce a novel scheme for UWB applications, named as Self Reference UWB (SR), which uses as reference signal the absolute value of a replica of the transmitted data signal multiplied by the Gaussian monocycle waveform. Compared to the conventional TR schemes which transmit two pulses (reference and data) for one data symbol, SR constructs the reference pulse from the transmitted data symbol, resulting in double data rates (as in DTR) and in lower complexity. Moreover, the SR scheme offers 3dBi performance improvement compared to the DTR and is characterised by the absence of the delay line (implemented both on TR and DTR scheme), which affects the complexity of the system, the power consumption and the synchronization between the transmitter and the receiver. The performance of the proposed UWB scheme is evaluated over a high-frequency (HF) channel model, used in high-data-rate UWB communication systems. Moreover, ISI, inter path/pulse interference (IPI) and noise are taken into account, resulting in a more realistic performance analysis. By evaluating the average bit error probability (ABEP) of the ARake, the DTR and the SR it is shown that the use of the received data pulse also as a reference leads in performance improvement and saving of computational resources without adding further power consumption.

The remainder of the paper is organized as follows. Channel model employed in the analysis is briefly described in Section II. In Section III, we present the mode of operation of the proposed receiver, while its performance is evaluated in Section IV. Finally, some concluding remarks are presented in Section V.
II. CHANNEL MODEL

The most suitable channel model for UWB applications and consequently for the evaluation of the performance of the proposed SR scheme, is the high-frequency (HF) model (accepted by the IEEE 802.15.3a standardization group), used in high-data-rate UWB communication systems. The HF UWB channel model is based on the Saleh-Valenzuela channel model [15] and is intended to represent the channel characteristics in the frequency range from 3.1 to 10.6 GHz [16]. According to this model, the received signal rays arrive in $L$ clusters each containing $K$ rays. The channel impulse response of the $i$-th realization is defined as

$$h_i(t) = X_i \sum_{l=0}^{L} \sum_{k=0}^{K} a_{k,l}^i \delta(t - T_{l}^i - \tau_{k,l}^i)$$

(1)

where $a_{k,l}^i$ is the tap weight associated with the $k$-th ray of the $l$-th cluster, $X_i$ is the log-normal shadowing and $T_{l}^i$, $\tau_{k,l}^i$ are the cluster and ray arrival times, respectively. In HF channel the arrival statistics of the MPCs are more sparse, in the sense that many paths may not carry any energy, which means that the first arriving path is not necessarily the strongest one. Regarding the distribution of the MPCs’ amplitude, it follows a lognormal distribution with variance that is independent of the path delays.

III. SYSTEM MODEL AND MODE OF OPERATION

A. Differential TR Scheme

In the following, the mode of operation of the DTR scheme will be described briefly for the reader’s convenience [14]. In DTR there is no separate reference pulse transmitted as in the conventional TR. Instead, the previously send data pulse is used as a reference for the next data signal under the assumption that the channel response remains the same for two consecutive symbols.

Analytically, the signal is differentially encoded using a delay line, as presented in Fig. 1, and after antipodal modulation it is transmitted in the following form

$$s_{DTR}(t) = \sum_{i=-\infty}^{\infty} m_i g_{tr}(t - iT_{f_{DTR}})$$

(2)

where $m_i = m_{i-1}b_{[i/N_s]}$, $g_{tr}(t)$ is the transmitted monocycle waveform that is non-zero only for $t \in (0, T_w)$, with $T_w$ and $T_{f_{DTR}}$ being the pulse and frame duration respectively. The data bits $b_{[i/N_s]} \in \{1, -1\}$ have equal probability and the index $[i/N_s]$ represents the index of the data bit modulating the
data waveform in the $i^{th}$ frame. In DTR each frame contains two monocycle waveforms, the reference and the data modulated one (in order for them to sustain the same channel conditions), with $T_d$ nano-seconds distance.

The transmitted signal passes through multipath channel (HF channel model assumes $K$ specular propagation paths, with the $k^{th}$ path’s propagation delay and amplitude being denoted by $\tau_k$ and $a_k$) and is corrupted by additive Gaussian noise (AWGN), $n(t)$.

The received signal of the differential system is

$$r_{DTR}(t) = \sum_{i=\infty}^{\infty} \sum_{k=1}^{K} a_k m_{i-1} b_{[i/N_s]} g_{rx}(t - iT_{f_{DTR}} - \tau_k) + n(u, t) \quad (3)$$

At the receiver (Fig. 1), the signal is autocorrelated, demodulated, differentially encoded (by using the $m$ data symbol as a reference for the $(m+1)$ data pulse which is generated $T_d$ nsecs later), passed through a low pass filter and reaches the threshold device where a decision is made upon the originally transmitted symbol.

The major advantages of the DTR scheme are that it introduces 3dB performance improvement and the double data rates that can be achieved (as no separate reference pulse is transmitted) compared to conventional TR. Moreover, the proposed structure does not suffer from propagation distortion, while channel estimation is not required as in Rake receivers.

On the contrary, in order for the differential encoding to be effective we assume that the coherence time of the channel equals the duration of two symbols which affects the performance of DTR [13]. Furthermore, the delay line which is required for the operation of the proposed structure is difficult to be implemented as most of the commercial available delay lines are not able to delay the signal in excess of the pulse period, working just up to the 30%-40% of the input pulse width, and only few ones allow delay times greater than the pulse width which is a prerequisite for the DTR. Additionally, the delay line increases the power consumption and causes interruption to the critical task of the synchronization of non-coherent scheme. Noisy reference is also an issue.

B. Self-Reference Scheme

In the proposed SR scheme only the data symbols are transmitted, without an extra reference signal (Fig. 3) resulting in one monocycle waveform per frame for SR, as presented in Fig. 2a.

Analytically, the transmitted signal of the SR is:
\[ s_{SR}(t) = \sum_{i=-\infty}^{\infty} b_{\lfloor i/N_s \rfloor} g_{tr}(t - iT_{f_{SR}}) \]  

where \( T_{f_{SR}} \) is the frame duration of SR and in the model we present is assumed to be shorter than the multipath delay spread \( T_{mds} \) resulting in interference between data pulses, which makes our system more realistic for UWB communications.

The transmitted signal passes through multipath channel and is corrupted by additive Gaussian noise. The received signal of the SR is

\[ r_{SR}(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{K} a_k b_{\lfloor i/N_s \rfloor} g_{rx}(t - iT_{f_{SR}} - \tau_k) + n(u, t) \]

As shown in Fig. 3, at the receiver the reference pulse is constructed by multiplying the absolute value of a copy of the received data pulse, to a gaussian monocycle which is non-zero for \( t \in (0, T_{uw}) \) and equal to one for the remaining time. Data pulse is correlated to the reference pulse and the output is demodulated and differential encoding is applied. A low pass filter is applied before the threshold device where the decision is made every \( N_s \) frames for recovering the originally transmitted symbols.

The SR frame is presented in Fig. 2b (data pulse +1 and −1 correspondingly) as processed at the transmitter and the receiver. We note that the reference signal remains positive for data symbol −1 as the absolute value of it is used to be multiplied by the gaussian monocycle. The output of the correlation of the data and the reference signal is presented at the figure.

The proposed system has two major advantages compared to the conventional TR schemes, the absence of the transmitted reference pulse, which doubles the data rate and the non-requirement of the delay line at the receiver, which is usually the most difficult part to implement in terms of complexity, precise synchronization and power consumption. Moreover, in the DTR scheme the reference signal depends on the previously received data pulse, hence the autocorrelation scheme at the receiver will be effective under the assumption that the channel response is the same over two consecutive symbols, which practically leads in a frame that contains two symbols. On the other hand, in the SR scheme the \( m \) reference pulse is constructed by using an elaborated replica of the \( m \) data symbol resulting in a frame with half duration of the corresponding in DTR. Consequently, the channel response is considered different for two consecutive symbols thus the proposed structure is able to cope with real UWB conditions without performance degradation.

To sum up, the proposed receiver introduce a new scheme that combines the advantages of the DTR, has lower complexity and power consumption, better synchronization and consequently better performance.
IV. PERFORMANCE ANALYSIS

In this section we evaluate the performance of the optimal Rake receiver (ARake) and the DTR scheme and we compare them with the proposed SR in terms of the ABEP. We consider realistic UWB channels characterised by high delay and frequency diversity, while the simulation conditions are the same as the one described in [17]. A second order derivative of the Gaussian monocycle with \( T_w = 0.7n \text{ sec} \) has been used with \( T_{f_{\text{DTR}}} = 10.75n \text{ sec} \), \( T_{f_{\text{SR}}} = 5.375n \text{ sec} \) and \( T_d = 8.75n \text{ sec} \) for DTR where the data pulse is delayed for serving as reference to the next symbol. ISI is taken into account in the analysis.

In Fig. 4a, the ABEP is plotted against the SNR assuming the CM1 channel model which refers to line of sight (LOS) in residential environments and was extracted based on measurements that cover a range from 7m to 20m, up to 10 GHz [18]. We note that the performance of ARake is the lower bound of the ABEP and serves only as a benchmark as it cannot be implemented in practice.

By inspecting the figure we conclude that the SR achieves a steady performance improvement of 3dB compared to DTR. This is a result of the resemblance of two consecutive channel responses which affects the critical task of data detection in conventional TR and DTR scheme. For instance, in case of four transmitted symbols and a channel coherence time of two symbols, the channel response will be the same for the first and the second data symbol and will differ between the second and the third one as they will experience different channel conditions. Consequently, the autocorrelation mechanism at the receiver will not be efficient as the channel impact will not be eliminated. On the other hand, the SR scheme assumes coherence time for the channel that equals one symbol duration as the reference pulse is constructed by the data symbol where the autocorrelation mechanism is applied, resulting in performance improvement in realistic UWB conditions where the channel response varies between two symbols.

Furthermore, in DTR, the reference pulse for the autocorrelation, decoding and detection procedure of each of the data symbol is based on the previously received pulse contrary to SR where the reference signal is dependent only to the data pulse. Hence, in DTR, when one symbol is incorrectly detected, the next one will be affected causing diminishment of the quality of the detected signal contrary to the SR scheme where the wrong detection of a symbol affects only itself and no further performance degradation is induced to the system. In parallel, the absence of the delay line at SR scheme ameliorates the synchronization mechanism which is critical for the performance of the system.

The results presented in Fig. 4b are based on CM2 channel model, which refers to non line of sight (NLOS) in residential environments with a coverage range from 7m to 20m [18]. The conclusions do not differ from those related to CM1 channel model. However, the performance degradation of all systems is
noticeable compared to CM1 and is a consequence of the severe scattering from which the signal suffers as we refer to a NLOS environment.

Same results are obtained for CM3 and CM4 channel models, which refer to NLOS indoor office environments while the models were based on measurements that cover a range from 3 to 28 m, for 2 to 8 GHz [18]. The results are depicted in Fig. 5a and 5b respectively. However, we may note that in CM4 channel model, the SR has a performance improvement compared to DTR of 2dB instead of 3dB. This happens because in extreme NLOS conditions, as the ones represented by CM4, due to severe scattering the first paths, which are multiplied to the gaussian monocycle, are not the strongest ones and they also suffer from noise.

V. Conclusions

A simpler scheme, called SR, was introduced which is able to achieve double data rates compared to conventional TR scheme, providing a noticeable advantage in dense multipath environments as UWB, and 3dB performance improvement compared to the DTR scheme. SR is an energy-efficient structure which requires less computational resources, compared to TR and DTR, as there is no need for implementing the delay line.

REFERENCES

[1] M. Z. Win and R. A. Scholtz, “On the energy capture of ultrawide bandwidth signals in dense multipath environments,” IEEE Commun. Lett., vol. 2, pp. 245–247, no. 9, Sept. 1998.
[2] R. C. Qiu, H. Liu, and X. Shen, “Ultra-wideband for multiple access communications,” IEEE Comm. Magazine, vol. 43, no. 2, pp. 80-87, Feb. 2005.
[3] J. D. Choi and W. E. Stark, “Performance analysis of rake receivers for ultra-wideband communications with PPM and OOK in multipath channels,” Proc. 2002 ICC, vol. 3, pp. 1969–1973, 2002.
[4] M. Z. Win and Z. A. Kostić, “Virtual path analysis of selective Rake receiver in dense multipath channels,” IEEE Commun. Lett., vol. 3, pp. 308–310, no. 11, Nov. 1999.
[5] M. Z. Win, G. Chrisikos, and N. R. Sollenberger, “Performance of Rake reception in dense multipath channels: implications of spreading bandwidth and selection diversity order,” IEEE J. Select. Areas Commun., vol. 18, pp. 1516–1525, no. 8, Aug. 2000.
[6] M. Z. Win and G. Chrisikos, Wideband Wireless Digital Communications ch. Impact of spreading bandwidth and selection diversity order on selective Rake reception, U.K.: Prentice-Hall, 2001, A. F. Molisch(ed.).
[7] D. Cassioli, M. Z. Win, F. Vatalaro and A. F. Molisch, “Low Complexity Rake Receivers in Ultra-Wideband Channels,” IEEE Trans. Wireless Commun., vol. 6, pp. 1265-1275, no. 4, April 2007.
[8] R. Hoctor and H. Tomlinson, “Delay-hopped transmitted-reference RF communications,” IEEE UWBST, pp. 265-269, 2002, Baltimore, MD.
[9] A. Rabbachin and I. Oppermann, “Comparison of uwb transmitted reference schemes,” *IEE Proc., Commun. (UK)*, vol. 153, no. 1, pp. 136–42, 2006.

[10] Y. Chao and R. A. Scholtz, “Ultra–Wideband Transmitted Reference Systems”, *IEEE Trans. on Vehic. Techn.* vol. 54, pp. 1556–1569, Sept. 2005.

[11] T. Q. S. Quek and M. Z. Win, “Analysis of UWB Transmitted–Reference Communications Systems in Dense Multipath Channels”, *IEEE J. Sel. Areas Commun*, vol. 23, pp. 1863–1874, no. 9, Sept. 2005.

[12] M. H. Chung and R. A. Scholtz, “Comparison of Transmitted– and Stored–Reference Systems for Ultra–Wideband Communications”, *IEEE Mil. Commun. Conf.*, vol. 1, pp. 521–527, Oct.–Nov. 2004.

[13] Alvaro Alvarez Vazquez, Beatriz Quijano Ruiz and Jose Luis Garcia Garcia, “Low Cost Variable Delay Line for Impulse Radio UWB Architectures,” *IST Mobile & Wireless Communications Summit*, Dresden 19-23 June 2005.

[14] Chao, Y. L. and R. A. Scholtz, “Optimal and suboptimal receivers for ultra-wideband transmitted reference systems,” *Proc. IEEE Global Telecommun. (Globecom ’03)*, vol. 2, pp. 759–763, San Francisco, CA, Dec. 2003.

[15] A. A. Saleh and R. A. Valenzuela, “A statistical model for indoor multipath propagation,” *IEEE J. Select. Areas Commun.*, vol. 5, pp. 128–137, Feb. 1987.

[16] J. R. Foerster, “Channel modeling sub-committee report final,” *in Tech. Rep. P802.15 02/490r1, IEEE 802.15 SG3a*, Feb. 2003.

[17] A. P. Doukeli, A. S. Lioumpas, G. K. Karagiannidis and P. V. Frangos, “Increasing the Efficiency of Rake Receivers for Ultra-Wideband Applications,” *ICCST WASET Conf.*, vol. 2, pp. 343–347, July 2009.

[18] A. F. Molisch, D. Cassioli, C. Chong, S. Emami, A. Fort, B. Kannan, J. Karedal, J. Kunish, H. G. Schantz, K. Siwiak and M. Z. Win, “A Comprehensive Standardized Model for Ultrawideband Propagation Channels,” *IEEE Trans. on Antennas and Propagation*, vol. 54, pp. 3151-3159, 11 Nov. 2006
Fig. 1. Transmitter and receiver scheme of DTR.
Fig. 2. (a) Transmitted frame of conventional TR scheme, DTR and SR, (b) Procedure followed by data signal (+1, −1).
Fig. 3. Transmitter and receiver scheme of SR.
Fig. 4. (a) ABEP vs SNR for LOS CM1 channel model (b) ABEP vs SNR for NLOS CM2 channel model.
Fig. 5. (a) ABEP vs SNR for NLOS CM3 channel model (b) ABEP vs SNR for NLOS CM4 channel model.