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# A novel Parzen probabilistic neural network based noncoherent detection algorithm for distributed ultra-wideband sensors

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ABSTRACT

Ultra-wideband (UWB) has been widely recommended for significant commercial and military applications. However, the well-derived coherent structures for UWB signal detection are either computationally complex or hardware impractical in the presence of the intensive multipath propagations. In this article, based on the nonparametric Parzen window estimator and the probabilistic neural networks, we suggest a low-complexity and noncoherent UWB detector in the context of distributed wireless sensor networks (WSNs). A novel characteristic spectrum is firstly developed through a sequence of blind signal transforms. Then, from a pattern recognition perspective, four features are extracted from it to fully exploit the inherent property of UWB multipath signals. The established feature space is further mapped into a two-dimensional plane by feature combination in order to simplify algorithm complexity. Consequently, UWB signal detection is formulated to recognize the received patterns in this formed 2-D feature plane. With the excellent capability of fast convergence and parallel implementation, the Parzen Probabilistic Neural Network (PPNN) is introduced to estimate a posteriori probability of the developed patterns. Based on the underlying Bayesian rule of PPNN, the asymptotical optimal decision bound is finally determined in the feature plane. Numerical simulations also validate the advantages of our proposed algorithm.



## 1. Introduction

Being capable of potentially providing extremely high-data-rates surpassing 1 Gbps, ultra-wideband has long been considered as a promising alternative for wireless broadband accessing in short-range applications (Yang and Giannakis, 2004; Roy et al., 2004). Currently, UWB serves as an appealing candidate to the emerging wireless personal area networks (WPAN; Siep et al., 2000). Moreover, the precise ranging and material penetration capability of UWB is of great significance for specific military applications, such as the high-precision radar (Kolenchery et al., 1998) and the through-wall target detection (Yarovoy et al., 2006). Additionally, UWB technique is also attractive to the distributed sensor networks, as the transmission strategies can be optimized according to the estimated geographical/range information (Shen et al., 2005). Nowadays, UWB sensor networks have been widely suggested to environmental pollution sensing and remote medical monitoring (Zasowski and Wittneben, 2009).

UWB impulse radio (UWB-IR) is one of the physical proposals considered for UWB communications, in which the emitted information bit is directly coded into baseband short duration pulses (Win and Scholtz, 1998, 2000). Owing to the enormous emission bandwidth, which always approaches several gigahertzes (GHz), the intensive multipath propagations have posed great challenges to low-complexity receivers designing, and hence, signal processing is generally vital to UWB receivers. Under the traditional coherent frameworks, a UWB receiver is supposed to capture dozens of resolvable multipath trajectories. Channel estimation algorithms for such a case may tend to be computationally unaffordable (Yang and Giannakis, 2004; Durisi and Benedetto, 2005; Lottici et al., 2002; Witrisal et al., 2009). Meanwhile, RAKE receiver also requires a population of correlators, which could bring considerable difficulties to hardware implementations (Rajeswaran et al., 2003; Cassioli et al., 2007). Consequently, these well-developed receiving architectures, originally for the narrow-band systems, may become inapplicable to UWB sensors especially for large-scale wireless sensor networks, which pay close attention to simple realizations. To overcome these challenges, the transmitted-reference (T-R) structure is introduced in Hoctor and Tomlinson (2002) and Franz and Mitra (2006). However, the transmission efficiency inevitably experiences an obvious degradation due to the dedicated reference pulse which carries no information. Additionally, the analog delay line in TR structure is difficult to realize with high accuracy, resulting in a deteriorated performance. As another appealing transmission strategy, on the other hand, multi-band orthogonal

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frequency division multiplexing (MB-OFDM) based UWB technique also has attracted much interest in recent years (Yang and Giannakis, 2004). Nevertheless, this multi-carrier based scheme still faces severe challenges from hardware implementations, especially when the typically enormous transmission bandwidth is taken into consideration. Specifically, the required complex RF devices always make the low-complexity and low-cost UWB applications unavailable. In this work, we mainly investigate the demodulation issues of UWB-IR system.

Recently, noncoherent receivers represented by energy detector (ED) have been motivated for simple UWB devices (Witrisal et al., 2009; D'Amico et al., 2007). Focusing on the received signal power other than the channel impulse response (CIR), ED essentially avoids the computational channel estimators accompanying the RAKE structures. Besides, ED is virtually immune to the clock timing estimation errors. This reduced requirement also leads to a low-sampling-rate analog to digital converters (ADC), further making the low-complexity UWB sensors possible (D'Amico et al., 2007). Meanwhile, the power consumption can be considerably reduced. If the partial channel state information (PCSI) is available, the average power decay profile (APDP) of multipath channels can be properly exploited as the weighting to received discrete samples, the performance can be further enhanced by 1–3 dB as is reported (Zasowski and Wittneben, 2009; Zasowski et al., 2006; Luecken et al., 2008). However, in order to extract and pass this local APDP information in distributed sensor networks, the required control channel (i.e. time and bandwidth) for this semi-coherent technique may become unaffordable in practice.

In order to reinforce detection performance and simultaneously alleviate requirements on a prior CSI, we develop a noncoherent UWB receiving architecture based on the Parzen probabilistic neural networks (PPNN). By thoroughly exploiting the intrinsic information of UWB channels, we firstly construct a characteristic spectrum from the received discrete sequences. Four distinguishing features are then extracted from this derived characteristic spectrum to effectively reflect the distinctions between UWB multipath signals and the channel noise. The established multidimensional feature space is further compressed to a two-dimensional plane in order to simplify complexity, and consequently, signal detection is transformed to classify two-group patterns data in a 2-D feature plane. Since most features are derived from the correlated random variables by complicated nonlinear transforms, basically it is hard to obtain the analytic probability density functions (PDFs) of these patterns. To overcome this adversity, the Parzen window technique is employed to estimate a posteriori PDF of the developed features. Furthermore, the probabilistic neural network is properly suggested to realize Parzen window estimator at an acceptable complexity, by taking advantages of its parallel computation ability. Finally, the asymptotically-optimal decision bound for patterns recognition (i.e. signals detection) is determined in the feature plane. With the rapid training speed and the excellent online incremental learning capability, the presented PPNN detecting algorithm can essentially approach the Bayesian optimality. Our nonparametric scheme is much superior to the existing noncoherent techniques although making no prior assumption on explicit channel parameters. The BER performance derived from numerical simulations verifies the advantages of our algorithm over ED and APDP in distributed applications.

The remainder of this paper is outlined as follows. In Section 2, we firstly analyze the indoor UWB channel characteristic and formulate a traditional UWB system model. We then develop a novel noncoherent signal processing architecture in Section 3. Based on the derived characteristic representations, UWB detection is realized through the Parzen probabilistic neural network in Section 4 from a pattern classification aspect. Section 5 is dedicated to numerical simulations and performance evaluations of the proposed algorithm. Finally, we conclude the whole paper in Section 6.

## 2. UWB system model

UWB generally characterizes the signals whose fractional bandwidth (i.e., its 3 dB bandwidth divided its center frequency) is large, typically over 0.25, or its instantaneous spectral occupancy exceeds 500 MHz (Yang and Giannakis, 2004). Without the use of local oscillators or frequency mixers, such UWB signals can be usually generated by driving an antenna with the extremely short pulses whose duration is on the order of a few nanoseconds to fractions of a nanosecond (Yang and Giannakis, 2004; Win and Scholtz, 1998). For this reason, UWB technique is often referred to as the short pulse or impulse radio systems.

### 2.1. UWB channel model

Taking the authorized UWB frequency band promulgated by US Federal Communications Commission (FCC) for example, the emission bandwidth may even approach 7.5 GHz (e.g. 3.1–10.6 GHz; Yang and Giannakis, 2004). Attributed to the enormous bandwidth and the resulting time resolution, the ability of UWB receivers to resolve different trajectories has been considerably enhanced. Therefore, the typical UWB propagations may exhibit some distinctive characteristics. First, the number of reflections arriving within the period of a very short impulse becomes smaller as the duration of the emission pulse gets shorter. Therefore, the distribution of the received envelope may not be described by the Rayleigh fading model (Win and Scholtz, 2002; Molisch, 2005). Second, since the multipath components may be resolved on a very fine time scale, the time of arrival (TOA) of the multipath reflections may not be continuous. This phenomenon could partly explain the "clustering" of multipath components observed in measurements (Molisch, 2005; Foerster, 2003).

For analysis convenience, in this work, we adopt the UWB channel modeling suggested by IEEE 802.15.3a working group (IEEE, 2003), which is based on the modified S–V channel model (Foerster, 2003). Four channel types for UWB applications in intensive multipath propagations are defined, i.e. CM1, CM2, CM3 and CM4. The expression of the uniform UWB CSI is given by

$$h(t) = X \sum_{l=0}^{L-1} \sum_{m=0}^{M-1} \alpha_{m,l} \delta(t - T_l - \tau_{m,l}) \quad (1)$$

where $L$ denotes the number of clusters, $M$ is the number of rays of each cluster, $\alpha_{m,l}$ is the fading coefficient of the $m$th path of the $l$th cluster, $X$ is the channel fading factor, $T_l$ is the arrival time of the $l$th cluster and $\tau_{m,l}$ is the delay of the $m$th path of the $l$th cluster relative to $T_l$. $T_l$ and $\tau_{m,l}$ has a Poisson distribution and $\alpha_{m,l}$ and $X_k$ are Log-normal random variables (Molisch, 2005; Foerster, 2003).

$$\begin{aligned} p(T_l \mid T_{l-1}) &= \Lambda \exp[-\Lambda(T_l - T_{l-1})], \quad l > 0 \\ p(\tau_{k,l} \mid \tau_{k-1,l}) &= \lambda \exp[-\lambda(\tau_{k,l} - \tau_{k-1,l})], \quad k > 0 \end{aligned} \quad (2)$$

We also assume UWB multipath channel to be quasi-static in our analysis, which means the amplitude coefficients $\alpha_{m,l}$ and delays $T_l + \tau_{m,l}$ remain invariant over one transmission burst, but are allowed to change across bursts. One typical realization of UWB channel has been illustrated in Fig. 1. Notice that the total signal power has been normalized, that is, $\Sigma_m \Sigma_l \alpha_{m,l}^2 = 1$.