A Weighted UWB Transmitted-Reference Receiver for Indoor Positioning Using MMSE Estimation[*]

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Abstract. Many emerging wireless intelligent network applications have the requirement of ranging and localization services besides data transfer. The impulse ultra-wideband (UWB) technology has accurate positioning capability as well as low to medium rate communication, so it is especially suitable in above applications. Due to implementation complexity concerns, UWB transmitted-reference (TR) receiver has become a good choice for this case recently. In this paper, considering the multipath components segment distribution characteristic of UWB received signals, a novel weighted UWB averaged TR receiver based on minimize-mean-square-error (MMSE) estimation for indoor positioning is presented by using segmentation-weighting-combination idea. Those segments which hold the intensive multipath signals are given the bigger weight coefficients, so that more useful multipath energy are captured meanwhile the noise product term is highly suppressed, thus the bit-error-rate (BER) performance of the receiver is efficiently improved. The suitable weight coefficients are obtained by using MMSE estimation via training data sequence. This receiver was analyzed and simulated in IEEE CM3 indoor multipath channel. The results show that it has superior detect performance compared with a conventional averaged TR receiver. The receiver can be used for those wireless intelligent network applications with indoor positioning capability.

Keywords: ultra-wideband (UWB) communications, weighted transmitted-reference (TR) receiver, minimize-mean-square-error (MMSE) estimation, indoor positioning.

1 Introduction

In recent years, ultra-wideband (UWB) wireless communication technology has aroused wide attention for its pulse characteristics essentially different from traditional narrowband sine-wave carrier and particular advantage of coexistence with the current

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communication system by its extremely low transmission power spectrum. Especially, an impulse UWB (IR-UWB) system adopts the nanosecond narrow pulse so that it has very accurate temporal and spatial information which can be used for precise time of arrival (TOA) estimation. The merit make it can not only realize robust low to high rate communications but also has accurate positioning capabilities. With the development of wireless communication and network technology, many new emerging applications can be generally classified as one kind of wireless intelligent network applications which often need ranging and positioning services besides medium data transfer [1][2], such as homeland security monitoring, remote patient healthcare, transportation object tracking, environment status monitoring, and assembling line automation, logistics package tracking, search and rescue (communications with fire fighters, or earthquake victims), and military team cooperative fighting, etc. UWB signaling is especially suitable in above application's requirements because it allows centimeter accuracy in ranging, as well as low-power and low-cost implementation of communication systems [3]. In these wireless intelligent networks, each node equipped with IR-UWB transceiver will be capable of a tremendous diversity of functionality such as sensing capabilities, signal processing, network protocol, short-range communication, and positioning capabilities. Some can be selected as beacon nodes, which are aware of their relative position, and others are peer nodes which can localize themselves by communicating with three or four beacon nodes, depending whether we are in presence of 2-dimensional or 3-dimensional positioning scenarios.

The types of IR-UWB receiver include the coherent RAKE receivers and the non-coherent transmitted-reference (TR) receivers. As the traditional RAKE receiver has high complexity in tap structure while serious multipath of UWB pulse at indoor situation, UWB TR receivers with simple structure & no channel estimation are more suitable for above wireless intelligent network applications and have been widely researched [4][5]. But a basic TR receiver has one major drawback of poor detection performance because the correlation template signal is formed by only one reference received waveform. In order to improve its performance, aiming at the approximate time-unvarying characteristic of UWB channel during a short period, reference [6] proposes an averaged transmitted-reference (ATR) receiver which transmits several repeated reference pulses before data signals and averages these reference received waveforms to decrease the noise level of correlation template, thereby improving the detection performance.

In this paper, by exploring and using the segments distribution characteristic of multipath components in UWB received signal, we proposed a further improved weighted ATR receiver base on minimize-mean-square-error (MMSE) estimation, which has better bit-error-rate (BER) performance. The idea of the proposed receiver is described in Section 2 and its structure is presented in Section 3. In Section 4, MMSE weight coefficient estimation is described and analyzed. Section 5 presents its performance simulation under multipath channel compare with a conventional ATR receiver and conclusions are drawn in Section 6.

2 Idea of Proposed Weighted ATR Receiver

The expression of bit-error-rate P_b of the ATR receiver [7] is derived as follows:

$$P_b = Q\left(\sqrt{\frac{N_s}{(\frac{N_r+1}{2N_r})(\frac{N_0}{E_p}) + \frac{2W\tau_{\max}}{4N_r}(\frac{N_0}{E_p})^2}}\right) \tag{1}$$

Therefore, the detection performance of the ATR receiver mainly depends on the noise product term $(\frac{N_0}{E_p})^2$ when the signal-to-noise ratio (SNR) of received signals is low. Because in UWB multipath channel impulse response $h(t)$ multipath components arrive in cluster and distribute sparsely on the time axis [8], if the time axis is divided into several time segments, certain time segments definitely contain more multipath components, while certain time segments contain fewer multipath components. Taking IEEE 802.15.3a of UWB indoor CM3 multipath channel as example [9], if the first 100ns is taken to be divided into five time segments, the distribution of the multipath components amplitude (absolute values) of received signals through the CM3 channel is shown in Fig. 1. There is no noise shown for clarity, and each peak is absolute value waveform of one UWB received pulse.

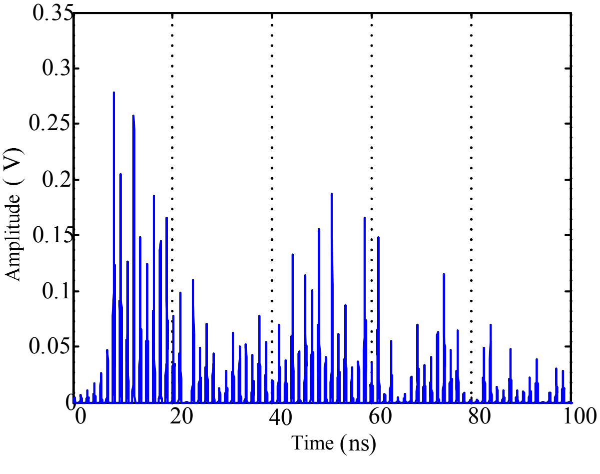

Fig. 1. Distribution of multipath components amplitude (absolute values) of received signals through CM3 channel in different time segments

In Fig.1, we can obviously see the distribution of signal energy of multipath components contained in different time segments: the first and the third time segments contain the most multipath signal energy, the second and the fourth time segments follows, and the fifth time segment contains the least multipath signal energy. Noise must exist in UWB received signals, especially when the SNR is low, so those time segments containing less multipath signal energy would contain stronger noise energy. Therefore, when we use the ATR receiver to carry out the correlation demodulation, these time segments contribute less for capturing useful signal energy but greatly increase noise signal energy in judgment item, and the noise product term $(\frac{N_0}{E_p})^2$ is increased resulting in obvious increase of the BER of the receiver.

In order to minimize the noise product term as much as possible to decrease the BER of the ATR receiver, aiming to above multipath components distribution characteristic of UWB received signal, we proposes a weighted ATR receiver by using segmentation-weighting-combination idea. It gives the segments different weights and gives the segment which holds the dense multipath components signal the bigger weight factor, thus the combined judgment item must include more useful multipath components energy and less noise energy ratio. Then the influence caused by noise-on-noise term in final judgment item is greatly reduced and according to equation (1), the receiver has better detection performance with lower $(\frac{N_0}{E_p})^2$ item. Moreover, we try to use training data sequence and MMSE estimation theory [10] to find the suitable the weight coefficients of segments.

3 Structure of Weighted ATR Receiver

The structure of the proposed weighted ATR receiver is shown in Fig. 2. In this receiver, the time axis for received signals is divided into several time segments, according to the amount of multipath signal energy contained by the time segment, its delayed product item in a correlator is multiplied by a corresponding weighting function $w(t)$, that is to say, the time segments containing more signal energy have larger weighted values, and the time segments containing less signal energy have smaller weighted values. After combined signals are integrated, more useful multipath signal energy will be captured and the SNR of output decision signals is increased, then BER performance of the receiver will be improved.

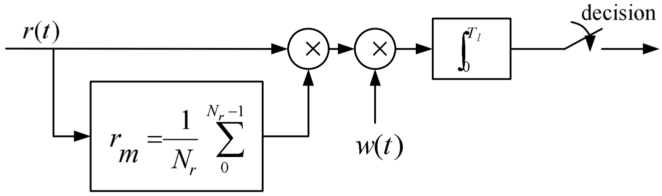

Fig. 2. Structure of weighted ATR receiver

In Fig. 2, suppose the time axis is $T_l = \tau_{\max}$ and T_l is divided into time segments with the number of Q, for the approximate time-unvarying channel characteristic during a short period, then time-varying weighting function $w(t)$ actually is a segmental constant function $w_q, 0 \le q \le Q$. For example, from multipath distributions of five time segments in Fig 1, we can see that the first and the third time segments obviously should be given the largest weights, the second and the fourth time segments smaller weights, and the fifth time segments smallest weight, so signal energy can be captured more efficiently.

In terms of the number of divided time segments, because the weight coefficient w_q of each time segment is an average weight based on all multipath components of the time segment, if the time axis is divided into more smaller time segments, then fewer multipath signals falls in each time segments, the selection of weight is more targeted, and the detection performance can be further improved. Theoretically, if the time axis is subdivided enough into the interval of a pulse width, each time segment only has one multipath component or no multipath component (weight is equal to zero), then there is no need to average weights, the weight can be determined only according to the amplitude of the multipath component, so it is more reasonable and efficient, and the receiver can obtain optimal performance. But if so, the time axis may need to be divided into hundreds of or thousands of time segments resulting in over complex structure and over high realization cost of the receiver. Therefore, an actual weighted ATR receiver generally divides the axis into limited several or dozens of time segments through balancing the BER performance and the complexity cost to obtain overall optimization.

4 MMSE Weight Coefficient Estimation

The detection performance of the weighted ATR receiver depends on appropriate selection of the weight coefficient w_q to a great extent. Theoretically, the weight which enables the correlator to output the largest instant SNR at sampling time is optimal, but it is extremely difficult to obtain above weight due to unpredictability of channel noise, so we can only use some suboptimal weight selecting method in practice [11]. The paper adopts a parameter estimation method based on minimize-mean-square-error estimation with strong practicability. In the method, a training data sequence c_n is transmitted, and the weight enabling $E\left|\hat{c}_n - c_n\right|^2$ to be smallest through training is the proper weight coefficient.

Suppose the length of the transmitted training data sequence is N , the n th modulated training data symbol is c_n , $c_n \in \{+1, -1\}$, pulses with the number of N_s represent a data symbol, and then it is derived that the n th data symbol $\hat{c}_n$ of weighted correlator output sampling is as follows:

$$\begin{aligned}\hat{c}_n &= \sum_{q=0}^{Q-1}\left(\frac{1}{N_s}\sum_{0}^{Ns-1}\int_{\frac{q}{Q}T_l}^{\frac{(q+1)}{Q}T_l} w_q\, r_m(t) r_{c,n}(t) d(t)\right)\\ &= \sum_{q=0}^{Q-1} w_q\left(\frac{1}{N_s}\sum_{0}^{Ns-1}\int_{\frac{q}{Q}T_l}^{\frac{(q+1)}{Q}T_l} r_m(t) r_{c,n}(t) d(t)\right)\\ &= \sum_{q=0}^{Q-1} w_q y_n(q)\end{aligned} \tag{2}$$

Where w_q is the weight of the q th time segment, $c_n \in \{0, 1, \cdots, Q-1\}$, $y_n(q)$ is the mean value of unweighted correlator output sampling of pulses with the number of N_s of the n th data symbol in the q th time segment. According to MMSE parameter estimation, the weight of corresponding time segment is obtained when the following cost function is a minimum.

$$E\,|\,\hat{c}_n - c_n\,|^2 = \frac{1}{N}\sum_{n=0}^{N-1}\left|\sum_{q=0}^{Q-1} w_q y_n(q) - c_n\right|^2 \tag{3}$$

By solve formula (2) to obtain weight coefficient as follows:

$$\begin{pmatrix} w_0\\ \vdots\\ w_q\\ \vdots\\ w_{Q-1}\end{pmatrix} = (\mathbf{YY^T})^{-1}(\mathbf{YC^T}) \tag{4}$$

Where $\mathbf{C^T} = \begin{pmatrix} c_1\\ \vdots\\ c_n\\ \vdots\\ c_{N-1}\end{pmatrix}$ is training data symbol vector, autocorrelation matrix is:

$$\boldsymbol{Y} = \begin{pmatrix} y_0(0) & \cdots & y_n(0) & \cdots & y_{N-1}(0)\\ \vdots & & \vdots & & \vdots\\ y_0(q) & \cdots & y_n(q) & \cdots & y_{N-1}(q)\\ \vdots & & \vdots & & \vdots\\ y_0(Q-1) & \cdots & y_n(Q-1) & \cdots & y_{N-1}(Q-1)\end{pmatrix} \tag{5}$$

In actual using of the weighted ATR receiver for positioning applications, reference data signals and weight training data sequence can be combined into a whole one, i.e., reference data signals with the number of N_r can be taken as the training data sequence of MMSE weight estimation, so certain transmission power can be saved, and the data transmission efficiency also can be improved.

5 Performance Simulation under Multipath Channel

Considering indoor positioning applications as a example in this paper, IEEE CM3 (4 ~ 10m, NLOS) of UWB indoor multipath channel is taken as a model, for single user, in the condition of ideal synchronization and additive-white-Gaussian-noise (AWGN) in channel, we simulated the BER performances of proposed weighted ATR receiver and compared it with a common ATR receiver. The inter-frame interference (IFI) and inter-symbol interference (ISI) are not included because many actual wireless positioning applications work at low to medium bit rates (up to 1 Mbps), so the pulse repetition interval (PRI) is large enough to ignore IFI & ISI influences.

For other simulation parameters, the number of reference pulses is $N_r = 100$, the numbers of divided time segments are respectively $Q = 5$ and $Q = 10$, MMSE weight estimation method is employed. An individual weight training data sequence (pseudo-random sequence with the length of 64) is adopted for simplify simulation, which is put at the head of each frame of ATR sending data, i.e., MMSE weight estimation by using training sequence is carried out firstly, and then averaging, weighting and correlation demodulation are performed. Performance simulation results obtained by this way are shown in Fig. 3. For comparison purpose, the performance curves of a common ATR receiver with $N_r = 100$ are given simultaneously. In Fig. 3, we simply denote the proposed weighted ATR receiver as WATR, so WATR-100, $Q = 5$ and $Q = 10$ represents the weighted ATR receivers of $N_r = 100$, $Q = 5$ and $Q = 10$ respectively.

In Fig. 3, we can see that compared with a common ATR receiver of $N_r = 100$, Both weighted ATR receivers of $N_r = 100$, $Q = 5$ and $Q = 10$ have improved performance in BER by inhibiting noise product term. When BER is equal to 10^{-4}, WATR of $Q = 5$ receiver has about 0.7dB of SNR gain than ATR receiver, and WATR of $Q = 10$ receiver has about 1.2dB of gain than ATR receiver, which shows that the more the number Q of divided time segments, the better BER performance. But along with the increase of Q, the increment of obtainable gain is smaller, while the complexity of MMSE weight estimation increases.

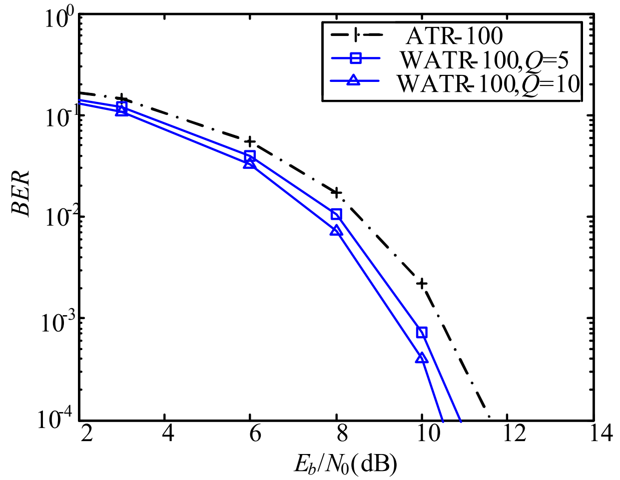

Fig. 3. Performance of weighted ATR receiver under CM3 multipath channel

In addition, in the lower SNR area of Fig. 3, WATR of $Q=10$ is always better than WATR of $Q=5$, and WATR of $Q=5$ is also always better than ATR, which shows that this weighting method still can improve performance in the condition of low SNR but has smaller increment gain at this time. The case is partially because the error of weight coefficient estimated based on MMSE is larger when SNR is low, and when SNR increases, the weight coefficient estimated based on MMSE becomes more accurate, and the performance gain of the weighted ATR receiver gets larger.

6 Conclusion

In this paper, considering the multipath components segment distribution characteristic of ultra-wideband received signals, a novel weighted UWB averaged TR receiver for indoor positioning based on MMSE estimation is presented by using segmentation-weighting-combination idea. Each segment has different weight; larger weights are given to the segments with intensive distribution of multipath components; weight coefficients of segments are gotten by using MMSE estimate via training sequence; so the receiver has strong practicality and easy to realize. Because the noise product term is inhibited, the bit-error-rate performance of the receiver is efficiently improved compared with a common ATR receiver, and the conclusion is further proved correct by the performance simulation results under IEEE CM3 multipath channel. This receiver can be used for those wireless intelligent network applications with indoor positioning capability.

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