A Novel TOA Estimation Using Multiple Masks Operation for Non-coherent IR-UWB Systems

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Abstract—This paper proposes a non-coherent time of arrival (TOA) estimation scheme using multiple Gold sequences on the existence of simultaneously operating piconets (SOPs). The proposed non-coherent receiver is composed of a series of energy collectors and low-bit analog to digital converters (ADCs). To mitigate the degradation of TOA estimation due to mutual interferences induced by multiple SOPs, the employment of Gold sequence is considered in this paper. Towards this, multiple masks operation (MMO) constructed by sub-Gold sequences are processed to enhance the quality of correlation property. Precisely, accumulation and overlapped multiplication processes make possible to improve the resolution so that the accurate TOA information can be achieved via proper comparison with a certain prescribed threshold. Furthermore, the search back window (SBW) method will be proposed to produce enhanced TOA estimation capability. The performance of the proposed SBW accompanied by sub-Gold sequence masks is verified by conducting proper simulations under two types of channel conditions. The simulation results show that the proposed scheme performs well even in a condensed indoor multipath environment on the existence of multiple SOPs.

I. INTRODUCTION

Recently demand has grown for precise positioning and ranging in short-range communication networks, and applications exploiting these features will play an important role in future wireless communication products. Regarding these trends, the IEEE (Institute of Electrical and Electronics Engineers) has established the Task Group 4 of the IEEE 802.15 W-PAN working group, whose major goal is to recommend a system with low-cost, low-power and precise positioning capability tailored for low-rate and short range wireless communications [1]. And to increase the accuracy of ranging and positioning, ultra-wideband (UWB) technique has been considered to be adopted to built up the current ranging performance [2][3].

Generally non-coherent method allows simple receiver structure including energy detector and easier synchronization method rather than the conventional coherent method. Thus it is advantageous to use the non-coherent method to fulfill the motivation of W-PAN.

While the TOA is estimated, the system might experience a non-line-of-sight (NLOS) channel, interferences of multiple SOPs, undesired clock drift and imperfect synchronization. These deficient factors may degrade the performance of ranging or positioning capabilities. In this paper, especially this paper focuses the exploitation of superior the TOA estimation on the existence of multiple SOPs.

Generally, PN sequences such as M-sequence, Ternary code and Gold sequence can be used to discriminate each piconet on the existence of multiple SOPs [6]. However, TOA information acquired by using a type of M-sequence might induce ambiguity on its result due to the inherent shift and add property of the M-sequence. Ternary code, a type of M-sequence with a zero side-lobe correlation property, was also proposed at the IEEE 802.15.4a TG to distinct each piconet [8][9]. It is well-known that this Ternary code can be utilized for both coherent and non-coherent ranging system.

To mitigate the erroneous TOA estimation, we propose an enhanced SBW based TOA estimation algorithm using MMO. After operating ADCs, multiple correlation processes are performed to enhance the correlation property, and then the timing of the first arrival path is estimated.

This paper is organized as follows. Section II describes the proposed ranging structure and its operational aspects. Section III introduces the proposed TOA estimation schemes using MMO together with SBW. The simulation results in Section IV verify the performance of proposed scheme. Finally, Section V contains concluding remarks.

II. OVERVIEW OF NON-COHERENT TRANSCIEVER FOR TOA ESTIMATION

In this paper, the frame format is based on alternate PHY of IEEE 802.15.4 [1].

Fig. 1. Preamble structure with a style of non-periodic pulse transmission
Due to the existence of surrounding, the received signal is comprised of direct and lots of reflected signals including background noise and interferences. In this paper, the interference is considered as a part of background noise. Then, the received signal $r(i)$ can be expressed as

$$r(i) = \sum_{n=1}^{N_r} a_n^{(m)} s(n) (t - \tau_d) + \sum_{r=1}^{L} a_n^{(m)} d(n) (t - \tau_r) + n(t)$$  \hspace{1cm} (2)$$

where $N_r$ is the number of piconets, the parameter $a_n^{(m)}$ and $\tau_d$ represent the strength of the direct path signal and its relative arrival time of a certain transmitted signal in $m$-th piconet, respectively. Also, $a_n^{(m)}$ and $\tau_r$ are the $n$-th reflected component and its corresponding time delay. $L$ is the number of multipath components associated to $m$-th piconet. In (2), $n(t)$ is the zero-mean AWGN.

After the usage of the square-law device as well as integration over $T_s$, the energy signal can be achieved as the following

$$e^{(i)}(\tau) = \int_{-T_s/2}^{T_s/2} r(i)(t) \, dt$$  \hspace{1cm} (3)$$

Upon the operation of multiple ADCs to received energy signal, the mean value denoted by $\bar{e}$ is measured by DC-offset estimator which is subsequently used as the reference value for the mapper. Precisely, the sampled data is mapped into 1 or -1 via comparing to the reference point. In sequel, regenerated 1-bit data steam is masked by Gold sequence, then the result is correlated with several template codes. These template codes are generated from main Gold sequence, $c_{m,\text{gold}}[n]$, and l-th sub-Gold sequence, $c_{l,\text{gold}}[n]$ , derived from main Gold sequence as the following

$$y_n[n] = \sum_{r=0}^{N_r} c_{m,\text{gold}}[n] y_n[n - \tau]$$  \hspace{1cm} (4)$$

$$y_n^{(l)}[n] = \sum_{r=0}^{N_r} c_{l,\text{gold}}^{(l)}[n] y_n^{(l)}[n - \tau]$$  \hspace{1cm} (5)$$

Correlated outputs are averaged over a symbol duration in parallel and then its result is normalized, i.e.,

$$s_{n}[i] = \frac{1}{N_r} \sum_{r=1}^{N_r} \sum_{j=1}^{T_s} \sum_{k=1}^{T_r} \frac{1}{T_r} \frac{1}{T_s} y_n^{(r)}[i]$$  \hspace{1cm} (6)$$

$$s_{l}^{(l)}[i] = \frac{1}{N_r} \sum_{r=1}^{N_r} \sum_{j=1}^{T_s} \sum_{k=1}^{T_r} \frac{1}{T_r} \frac{1}{T_s} y_n^{(l)}[i]$$  \hspace{1cm} (7)$$

In (6) and (7), $\Delta t$ is sampling duration, $N_r$ denotes the number of symbols in preamble. In addition, two different kinds of averaged outputs are subsequently multiplied by each other sample-by-sample, so that this gives more enhanced correlation property. Along this process, the first coarse index whose corresponding value is exceeding predetermined threshold $\eta$ can be mathematically expressed as the following

$$\text{TOA} = \arg \min_{i \in [1 \ldots N_r]} \left\{ s_{n}[i] \times \prod_{i=1}^{N_r} s_{l}^{(l)}[i] \geq \eta \right\}$$  \hspace{1cm} (8)$$

where $N_r$ is the number of sub-Gold sequence. Referring to coarse index of first arrival, adequate SBW, i.e. $W_{sb}$, which is
[TOA-M, TOA-M-1, ..., TOA], are established so as to make weak TOA component fortified, and relevant process as the following

\[ V_{\text{index}}(i) = \text{find}(W_{\text{sb}}(i) > \beta); \]
\[ W_{\text{sb}}(V_{\text{index}}) = \frac{f_n}{s_n}; \]
\[ W_{\text{sb}} = \frac{N \cdot f_n}{s_n}; \]

End

Fig. 3. SBW execution procedure

Here \( M \) is the size of SBW, \( N \) is the number of iterations and \( \text{find}() \) denotes the function for exploiting indexes corresponding value exceeding pre-defined threshold. In Fig.3, \( V_{\text{index}} \) indicates the index of value larger than \( \beta \) among \( W_{\text{sb}} \) whose value is converted into a constant \( \varepsilon \) and then normalized. Finally, a fine TOA index can be achieved by

\[ \text{TOA}_F = \arg \min_{i=1:M} \{ W_{\text{sb}}(i) \geq \alpha \} \quad (9) \]

In (9), \( \alpha = N(V_{\text{min}}/\varepsilon-V_{\text{min}}) \) is the secondary pre-determined threshold. Here, \( V_{\text{min}} \) is the demanded minimum value of TOA. To help the comprehension, Fig. 4 illustrates the execution diagram of the proposed TOA determination process through MMO together with SBW.

![Fig. 4. The execution diagram of proposed TOA determination process](image)

IV. SIMULATION RESULTS

To verify the performance of the proposed TOA estimation scheme, two distinct channel models, i.e., residential LOS environment (CM1) and industrial NLOS environment (CM8), approved by IEEE 802.15.4a Task Group [10], are considered in our simulations. Obeying the typical root mean square (RMS) delay spread, \( T_f \) and \( T_c \) are specified by 60 nsec and 15 nsec, respectively. Upon the recent specification of IEEE 802.15.4a, the other detailed simulation parameters are listed in Table 1.

For the sake of comparison, the case of using Ternary code is considered for the distinction of piconet. It is well known that ternary code becomes equivalent to M-sequence while the non-coherent receiver having energy detection is utilized. Since the non-coherent receiver is considered in our paper, the M-sequence of length 63 is used instead of ternary code.

Fig. 5 depicts the two different kinds of normalized sequence after correlation with respect to results between conventional and proposed methods in a CM1 environment.

![Fig. 5. Comparison of the normalized correlation results between the two methods in a CM8 environment](image)

Here, SNR and SOP are set to 0 dB and 4, respectively. In Fig. 5, the label “CONV” means the conventional scheme using single correlation and averaging process, and the label “PROP” indicates the proposed method through MMO together with SBW. As shown in Fig. 5, it is apparent that the proposed method is less sensitive to the prescribed threshold than the conventional method. Provided that repetitive normalization process is accomplished in SBW, TOA can be accurately estimated while the strength of the LOS path is relatively weak.

In peer-to-peer situation, Fig. 6 shows the behavior of the CDF (Cumulative Density Function) characteristic of the TOA

![Fig. 6. Comparison of the CDF characteristic of the TOA](image)
error for both CM1 and CM8 environments. The value of SNR is set to 6dB. Both cases in Fig. 6 show that the proposed method performs better than the conventional method in the sense of minimization of TOA error.

Fig. 7 shows the behavior of the CDF curves of the TOA error corresponding to each spread code in both CM1 and CM8 channels. Here, SNR and SOP are set to 10 dB and 0, respectively. As illustrated in Fig. 7, probability that the TOA error is under 50cm in a CM1 environment is about 88 percent for the proposed scheme. Considering that the employed ADC’s resolution is about 66 cm, it can state that the capability of TOA estimation is acceptable. In both channel cases, the conventional method using M-sequence performs slightly better than that using the Gold sequence in CM1 case. Clearly, this is due to the fact that M-sequence has good correlation property showing zero side-lobe characteristic. Whereas, the proposed method using Gold sequence is always better than the conventional in the aspect of minimizing TOA error.

To verify the effectiveness of the proposed method in the existence of multiple SOPs, Fig. 8 is revealed to show the behavior of the CDF curves of the TOA error. Here, the number of SOPs is set to 4. As shown in Fig. 8, it is easy to notice that the M-sequence-based TOA estimation method works poorly due to the shift and add properties. Whereas, it can conclude that the proposed method performs better even in multiple SOP situation.

![Graph showing the CDF of the TOA error for different spread codes in CM1 and CM8 channels (SNR = 10 dB, SOP = 0)](image1)

![Graph showing the CDF of the TOA error for different spread codes in CM1 and CM8 channels (SNR = 10 dB, SOP = 4)](image2)

V. CONCLUSION

This paper proposes a novel non-coherent TOA estimation scheme using multiple Gold sequences in the existence of multiple SOP. To mitigate IPI, the pulse pattern in a style of non-periodic pulse transmission is purposely restructured. In order to improve the accuracy of TOA estimation, the proposed estimation scheme has deserved to enhance the correlation property by employing multiple sub-Gold sequence masks. According to the simulation results, it can conclude that the proposed scheme using Gold-sequence together with its decimated versions used for multiple mask operations performs well even in a condensed multipath indoor environment as well as in the existence of multiple SOPs.

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VI. REFERENCES