A Study on Filterings in Non-coherent TOA Estimation in TH-UWB-IR Systems

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***Abstract*—In this paper, we consider time-of-arriaval (TOA) estimation based on energy detection of time hopping-ultra wideband-impulse radio (TH-UWB-IR) signals. The accuracy of TOA estimation is largely degraded in the presence of strong multiuser interference (MUI) and intersymbol interference (ISI). As methods to mitigate the effects of MUI and ISI on TOA estimation, applying filter to the received signal energy is shown to be effective. As filters, minimum filter and median filter have been applied to TH-UWB-IR. However, anything other than the two filters has not been reported. It has not also been clarified where and what filter we should use in the TOA estimation. In this paper, we evaluate the TOA estimation accuracy of TH-UWB-IR system with the following filters: median filter, minimum filter, and outlier filter. We clarify where we apply each filter in the TOA estimation.**

I. Introduction

Time hopping-ultra wideband-impulse radio (TH-UWB-IR) helps to separate individual multipath components better, and provides more accurate time-of-arriaval (TOA) estimation than narrowband signals. In sensor networks that are expected as one of the applications of TH-UWB-IR, low complexity TOA estimation is required. TOA estimation based on energy detection of TH-UWB-IR has low complexity [1]. In TOA estimaion based on energy detection, a receiver first receives the signal from the transmitter with square-law detector, and estimates TOA based on its energy. The accuracy of TOA estimation is greatly degraded in the presence of strong multiuser interference (MUI) and intersymbol interference (ISI). As methods to mitigate the effects of MUI and ISI on the TOA estimation, applying filter to received signal energy is shown to be effective. In [2] applying minimum filter to the received signal energy is shown to be effective. Minimum filter outputs the minimum value in the filter. In [2] minimum filter is applied to the received signal energy after the received signal energy is correlated with TH codes. It is reported that applying minimum filter improves the accuracy of TOA estimation. Also, in [3], applying median filter to the received signal energy is shown to be effective. Median filter outputs the median value in the filter. In [3] median filter is applied to the received signal energy before the received signal energy is correlated with TH codes. It is reported that applying median filter improves the accuracy of TOA estimation. In [2] it is reported that applying minimum filter after the received signal energy being correlated with TH codes improves the accuracy of TOA estimation larger than applying median filter after that.

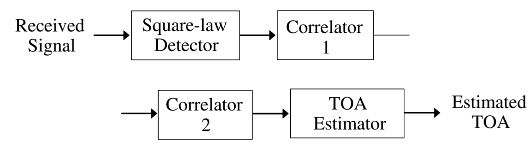

Fig. 1. Simple system block diagram of TOA estimation method based on energy detection.

Anything other than the two filters has not been reported in TOA estimation of TH-UWB-IR system. It has not also been clarified where and what filter we should use in the TOA estimation.

In this paper, we clarify where we apply each following filter in the TOA estimation of TH-UWB-IR system: minimum filter, median filter, and outlier filter, where outlier filter removes the value whose deviation is maximum in the filter. There are two places that each filter can be applied: beore the received signal energy is correlated with TH codes, or after that. We evaluate the TOA estimation accuracy with the three filters applied in each position by computer simulations on CM1 (residential LOS) channel model of IEEE 802.15.4a. By results of the simulations, we show that we had better apply minimum filter before the received signal energy being correlated with TH codes when the desired user's E_b/N_0 is high, and apply no filter when the desired user's E_b/N_0 is low.

This paper is organized as follows. In Section 2, the system model of this research, TOA estimation method based on energy detection, and its problems are described. In Section 3-5, TOA estimation method that applys minimum filter, median filter, and outlier filter, respectively, are described. In Section 6, we discuss simulation results. Finally, this paper concludes in Section 7.

II. TOA Estimation Method Based on Energy Detection

Fig. 1 shows the simple system block diagram of the TOA estimation method based on energy detection. TH-UWB-IR signal is transmitted from the transmitter, and the receiver is a square-law detector. The number of pulses per frame is one. Fig. 2 shows the transmitting waveform and an example of corresponding output of the square-law detector, $r(t)$, per symbol for the total number of pulses

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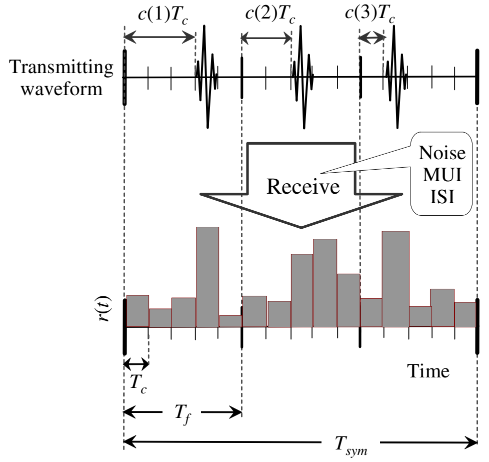

Fig. 2. Transmitting waveform and an example of corresponding output of the square-law detector ($N_s = 3$).

per symbol, $N_s = 3$, where $c(i)$ is the TH code for the ith frame, T_c is the chip duration, T_f is the frame duration, and T_{sym} is the symbol duration. The time period over which the output of the square-law detector is integrated is T_b, and the pulse duration of the transmitting waveform is equal to T_c. When the signal is received, noise, MUI, and ISI are added to it.

Next, $r(t)$ is input to the correlator 1, and is correlated. When $r(t)$ is input to the correlator 1, first, N_s outputs among $r(t)$ corresponding to the TH code are summed up in each symbol, and they are denoted by $x(n, j, i)$.

$$x(n, j, i) = \int_{(j-1)T_{sym}+(i-1)T_f+\{c(i)+n-1\}T_c}^{(j-1)T_{sym}+(i-1)T_f+\{c(i)+n\}T_c} |r(t)|^2 dt, \tag{1}$$

where n is the time index (the chip index), j is the symbol index ($j \in \{1, 2, \ldots, R\}$, R is the number of repetitions of each symbol), and i is the frame index ($i \in \{1, 2, \ldots, N_s\}$). Then, $x(n, j, i)$ is input to the correlator 1. That is, $x(n, j, i)$ of N_s pieces are summed at each symbol, and the sum is denoted by $z(n, j)$.

$$z(n, j) = \sum_{i=1}^{N_s} x(n, j, i) \tag{2}$$

Next, $z(n, j)$ is input to the correlator 2. That is, $z(n, j)$ of R pieces are summed at each time index, and the sum is denoted by $Z_{sum}(n)$.

$$Z_{sum}(n) = \sum_{j=1}^{R} z(n, j) \tag{3}$$

Finally, TOA estimation is done by using $Z_{sum}(n)$. If the estimaed time index including the leading edge is assumed to be $\hat{n}_{DP}$, it becomes

$$\hat{n}_{DP} = \min\left\{ n \,\middle|\, Z_{sum}(n) > \xi \cap \max\{n - W_{sb} + 1, 1\} \le n \le n_{max} \right\}. \tag{4}$$

The method to obtain $\hat{n}_{DP}$ is illustrated in Fig. 3, where ξ is the threshold. In this paper, we use ξ optimized by computer simulations [6]. n_{max} is the time index, n, for the maximum $Z_{sum}(n)$ within the range of $1 \le n \le \frac{3}{2}\frac{T_f}{T_b}$, W_{sb} is the search back window length. The search

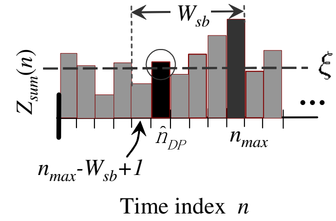

Fig. 3. TOA estimaton

back window length is a search range used when $\hat{n}_{DP}$ is searched.

If the estimated TOA is assumed to be $\hat{t}$, it becomes

$$\hat{t} = \hat{n}_{DP} T_c. \tag{5}$$

The accuracy of TOA estimation is greatly degraded in the presence of strong MUI and ISI. This is because the received signal energy for the time index in the absence of the desired user's signal may become large or small owing to MUI and ISI. Then, the TOA estimation method that can mitigate the effects of MUI and ISI is desired. In Section 3-5, as methods to mitigate the effects of MUI and ISI on the TOA estimation, TOA estimation methods applying various filters to received signal energy are explained.

A. *Minimum Filter*

As a method to mitigate the effects of MUI and ISI, applying minimum filter to the received signal energy has been reported [2]. Minimum filter outputs the minimum value in the filter. In [2] minimum filter whose length is W_{min} is inserted just before $z(n, j)$ is input to the correlator 2. We refer to this insert position as "after correlator 1". Fig. 4 shows a simple system block diagram of the TOA estimation method based on energy detection with minimum filter after correlator 1. Fig. 5 shows the processing of the minimum filter for $W_{min} = 3$. Window index in Fig. 5 is an index in the filter window. In Fig. 5, $z(n, 3)$ for the time index, n, in the absence of the desired user's signal becomes large seriously because of MUI and ISI. However, in $z(n, j)$ after the minimum filter is applied, $z_{min}(n, j)$, the effects of MUI and ISI on $z(n, 3)$ are mitigated. That is, within the filter window, even when $z(n, j)$ becomes larger seriously because of MUI and ISI at the time index in the absence of the desired user's signal, the effects of MUI and ISI can be mitigated if there is $z(n, j)$ for which those effects are not large. $z_{min}(n, j)$ is expressed as

$$z_{min}(n, j) = \min\left\{ z(n, j), z(n, j+1), \ldots, z(n, j+W_{min}-1) \right\}, \tag{6}$$

where $j \in \{1, 2, \ldots, R - W_{min} + 1\}$.Then, $z_{min}(n, j)$ is input to the correlator 2, and $Z_{sum}(n)$ is obtained. Finally, TOA estimation is done by using $Z_{sum}(n)$.

In [2] it is reported that applying minimum filter improves the accuracy of TOA estimation. The performance improvement by minimum filter is remarkable when the interference user's $E_b/N_0 = 0, 5, 10$ dB, and increases as the desired user's E_b/N_0 becomes higher. Also, it is reported that applying minimum filter after correlator

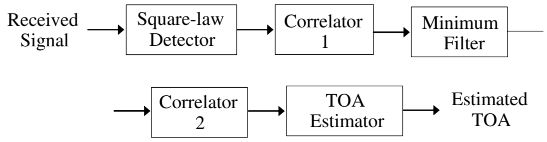

Fig. 4. Simple system block diagram of the TOA estimation method based on energy detection with minimum filter after correlator 1.

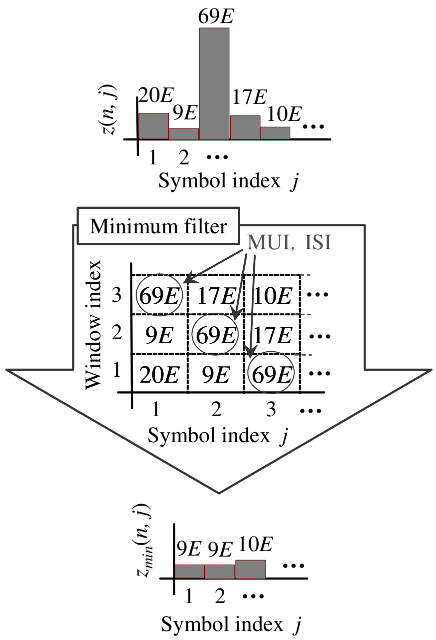

Fig. 5. Processing of minimum filter after correlator 1 ($W_{min} = 3$, E: signal energy).

1 improves the accuracy of TOA estimation larger than applying median filter after that.

B. Median Filter

As a method to mitigate the effects of MUI and ISI, applying median filter to the received signal energy has been reported [3]. Median filter outputs the median value in the filter. In [3] median filter whose length is $W_{med} = N_s$ is inserted just before $x(n, j, i)$ of N_s pieces is input to the correlator 2. We refer to this insert position as "before correlator 1". Fig. 6 shows a simple system block diagram of the TOA estimation method based on energy detection with median filter before correlator 1. Fig. 7 shows the processing of the median filter for $N_s = W_{med} = 4$. In Fig. 7, $x(n, j, 1)$ for the time index, n, in the presence of the desired user's signal is small seriously because of MUI and ISI. However, in $x(n, j, i)$ after the median filter is applied, $x_{med}(n, j, i)$, the effects of MUI and ISI on $x(n, j, 1)$ are mitigated. That is, within the filter window, even when $x(n, j, i)$ becomes smaller or larger seriously because of MUI and ISI, the effects of MUI and ISI can be mitigated if the number of $x(n, j, i)$ for which those effects are not large is smaller than that for which those effects are large. $x_{med}(n, j, i)$ is expressed as

$$x_{med}(n, j, i) = \text{median}\Big\{x(n, j, 1), x(n, j, 2), \ldots, x(n, j, N_s)\Big\}, \tag{7}$$

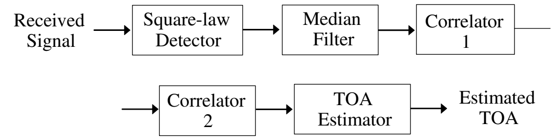

Fig. 6. Simple system block diagram of the TOA estimation method based on energy detection with median filter before correlator 1.

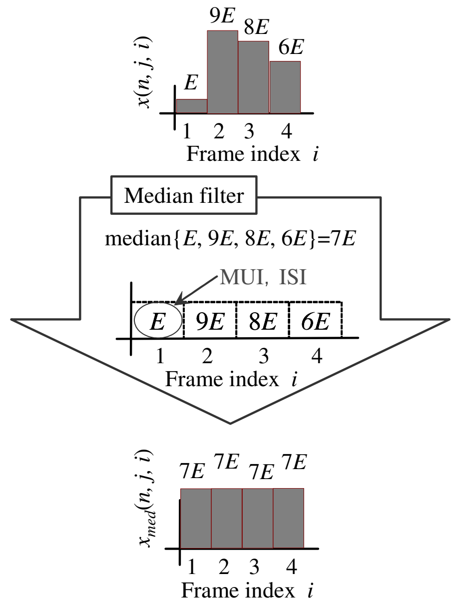

Fig. 7. Processing of median filter before correlator 1 ($N_s = W_{med} = 4$, E: signal energy).

where median$\{\cdot\}$ is a function that outputs the median value. Then, $x_{med}(n, j, i)$ is input to the correlator 1, and $z(n, j)$ is obtained.

In [3] it is reported that applying median filter improves the accuracy of TOA estimation. The performance improvement by median filter is remarkable when the interference user's $E_b/N_0 = 0, 5, 10$ dB, and increases as the desired user's E_b/N_0 becomes higher.

C. Outlier Filter

Outlier filter described in this paper removes the value whose deviation is maximum in the filter. Fig. 8 shows a simple system block diagram of the TOA estimation method based on energy detection with outlier filter before the correlator 1. Fig. 9 shows the processing of the outlier filter for $N_s = W_{out} = 4$. In Fig. 9, $x(n, j, 2)$ for the time index, n, in the presence of the desired user's signal is small seriously because of MUI and ISI. However, in $x(n, j, i)$ after the outlier filter is applied, $x_{out}(n, j, i)$, the effects of MUI and ISI on $x(n, j, 2)$ are mitigated. With outlier filter, MUI and ISI can be mitigated in both cases as follows:

- The case where there is $r(t)$ that becomes larger for the time index in the absence of the desired user's signal: false alarm in the absence of the desired user's signal
- The case where there is $r(t)$ that becomes smaller for the time index in the presence of the desired user's

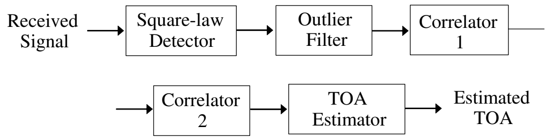

Fig. 8. Simple system block diagram of the TOA estimation method based on energy detection with outlier filter before correlator 1.

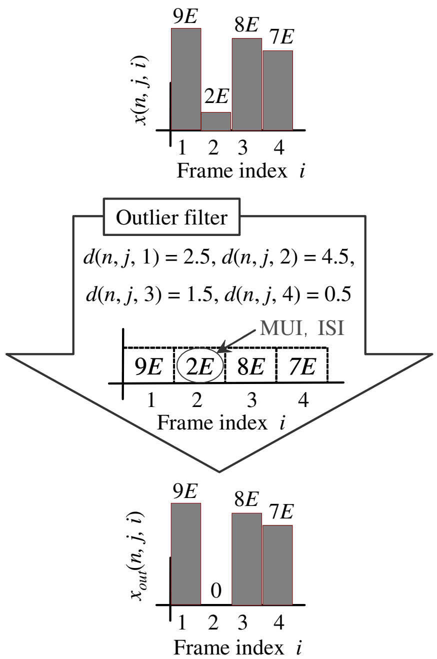

Fig. 9. Processing of outlier filter before correlator 1 ($N_s = W_{out} = 4$, E: signal energy).

signal: signal missing in the presence of the desired user's signal

$x_{out}(n, j, i)$ is expressed as

$$x_{out}(n, j, i) = 0 \quad \text{if} \quad d(n, j, i) = \max\{d(n, j, 1), d(n, j, 2), \ldots, d(n, j, N_s)\}, \tag{8}$$

where $d(n, j, i)$ represent

$$d(n, j, i) = \left| x(n, j, i) - \frac{\sum_{i=1}^{N_s} x(n, j, i)}{N_s} \right|. \tag{9}$$

Then, $x_{out}(n, j, i)$ is input to the correlator 1, and $z(n, j)$ is obtained.

III. Simulation Results

In simulations presented in this section, the CM1 channel model of IEEE 802.15.4a is employed [4]: Residential LOS, cluster arrival rate is 0.047 clusters/ns, ray arrival rate is 1.31 rays/ns, cluster decay factor is 22.61 ns, ray decay factor is 12.53 ns. Following three environments are simulated: interference user is absent, the interference user's E_b/N_0 is $10, 20$ dB. In each environment, the performances of the TOA estimation with the three filters at the two insert positions are evaluated respectively:

- The case with outlier filter before correlator 1
- The case with minimum filter before correlator 1
- The case with median filter before correlator 1
- The case with outlier filter after correlator 1
- The case with minimum filter after correlator 1
- The case with median filter after correlator 1
- The case with no filter

We evaluate mean absolute error (MAE) of TOA estimations over 500 realizations. Transmitting UWB-IR signal is the fifth-derivative of the Gaussian pulse [5]. The other simulation settings are as follows: sampling frequency is 20 GHz, $T_{sym} = 640$ ns, $T_f = 128$ ns, $T_b = 4$ ns, the length of each filter inserted before the correlator 1 is $W_{min} = W_{med} = W_{out} = N_s = 5$, the length of each filter inserted after the correlator 1 is $W_{min} = W_{med} = W_{out} = 4$, the number of interference user is one, TH code of the desired user is $c(i) = [4, 2, 5, 1, 1]$, TH code of the interference user is $c(i) = [1, 4, 2, 5, 1]$, and the number of replication of symbols is $R = 80$ [2]. The length of each filter is optimized by computer simulation.

Figs. 10-12 show the MAE results when interference user is absent, the interference user's E_b/N_0 is $10, 20$ dB, respectively. Horizontal axes represent the desired user's E_b/N_0. Vertical axes represent MAE (Mean Absolute Error). From these figures, we can see the following things:

1) When interference user is absent
   - 1-a) Each filter can not improve the MAE performance.
2) When the interference user's $E_b/N_0 = 10$ dB
   - 2-a) The MAE performance with minimum filter before correlator 1 is the best.
   - 2-b) All three filters before correlator 1 can respectively improve the MAE performance when the desired user's E_b/N_0 is low.
   - 2-c) When the desired user's E_b/N_0 is high, for each filter, inserting it before correlator 1 can improve the MAE performance larger than that after correlator 1.
   - 2-d) The MAE performance when the desired user's $E_b/N_0 = 22$ dB is inferior to that when the desired user's $E_b/N_0 = 19$ dB
3) When the interference user's $E_b/N_0 = 20$ dB
   - 3-a) All three filters before correlator 1 can respectively improve the MAE performance when the desired user's E_b/N_0 is high, but degrades that when the desired user's E_b/N_0 is low.
   - 3-b) When the desired user's E_b/N_0 is high, the MAE performance with minimum filter before correlator 1 is clearly the best.
   - 3-c) When the desired user's E_b/N_0 is high, for each filter, inserting it before correlator 1 can improve the MAE performance larger than that after correlator 1.

(2-a), (3-b) show that applying minimum filter before correlator 1 is the best approach to mitigate the effects of MUI. Also, the higher the interference user's E_b/N_0 is, the more the minimum filter before correlator 1 can improve the MAE performance when the desired user's E_b/N_0 is high. (2-c), (3-c) show that mitigating the

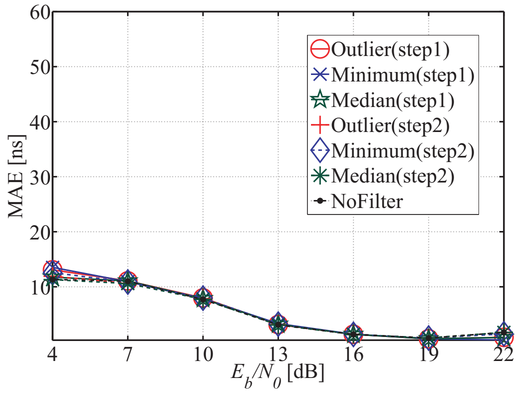

Fig. 10. MAEs of seven approaches with no interference.

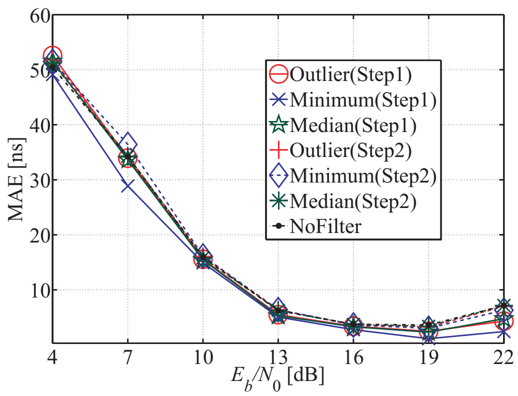

Fig. 11. MAEs of seven approaches with interference user's $E_b/N_0 =$ 10 dB.

effects of MUI before correlator 1 can improve the MAE performance larger than that after correlator 1 when the desired user's E_b/N_0 is high. This is because we can see interference effects on pulses more correctly than on outputs of correlator 1. (2-d) results from that increasing the desired user's E_b/N_0 also increases the energy of autocorrelation sidelobes.

Therefore, it is efficient to apply no filter when the desired user's E_b/N_0 is low, and to apply minimum filter before the received signal energy being correlated with TH codes under the other environments.

IV. Conclusion

In this paper, we evaluate the TOA estimation accuracy of TH-UWB-IR system with the following filters applied in each position by simulations: median filter, minimum filter, and outlier filter. By results of the simulations, we show that we had better apply minimum filter before the received signal energy being correlated with TH codes when the desired user's E_b/N_0 is high, and apply no filter when the desired user's E_b/N_0 is low.

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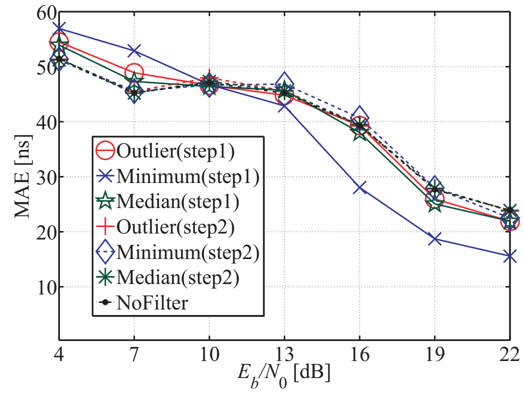

Fig. 12. MAEs of seven approaches with interference user's $E_b/N_0 =$ 20 dB.

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