Effect of clock offset on an impulse radio ultra wideband ranging system with comparators

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Abstract: Impulse radio ultra wideband (IR-UWB) can achieve high resolution in ranging because it uses a very short pulse with a duration of less than 1 ns. In order to reduce cost and power consumption, a ranging system with high-speed comparators has been proposed. In this system, it is necessary to reduce noise power through averaging the comparator outputs. The authors evaluate the effect of clock offset on the averaging process, and a two-stage averaging scheme for the IR-UWB ranging system is proposed. Through computer simulation, it is proved that the proposed scheme can reduce the effect of the clock offset with appropriate numbers of initial averaging.

1 Introduction

Impulse radio ultra wideband (IR-UWB) uses a very short pulse with a duration of less than 1 ns [1, 2]. Therefore it can achieve high resolution ranging in the order of tens of centimetres. The resolution of an IR-UWB ranging system is higher as compared with wireless LAN-based ranging systems or the other wireless-based ranging systems [3, 4].

One of the problems regarding the UWB positioning system is the implementation of receiver circuits. The IR-UWB system requires synchronisation circuits with the accuracy of tens of picoseconds [5]. It is very difficult to implement the receiver with such high accuracy in analogue circuits. On the other hand, if the UWB signal is processed in the digital domain, it is hard to reduce the cost and power consumption of the receiver with high-speed and high-resolution A/D converters (ADCs).

Therefore an IR-UWB ranging system with high-speed comparators has been proposed [6, 7]. In this system, it is necessary to average the outputs of the comparator in order to reduce noise power and to detect the pulse signal. Ideally, if the number of averaged pulses increases, the signal-to-noise ratio (SNR) improves. However, if a clock offset between the transmitter and the receiver exists, the averaging process actually decreases the signal power.

This paper attempts to evaluate the effect of the clock offset on the ranging system. A two-stage averaging scheme for the IR-UWB ranging system is also proposed. The proposed scheme separates the averaging process into two stages, the initial stage and the second stage. In the initial stage, the received signal is averaged and in the second stage the detected pulse timing is averaged. By limiting the numbers of the initial averaging the proposed scheme reduces the effect of the clock offset.

This paper is organised as follows. In Section 2 we present the model of the IR-UWB ranging system. Numerical results through computer simulation are shown in Section 3. In Section 4 we give our conclusions.

2 System model

Fig. 1 shows the system model assumed in this research. An active RF tag system is assumed and a one-way ranging-time difference of arrival (OWR-TDOA) method is employed for simplification of the transmitter. At the receivers, the transmitted signal is received by the Rx antennas and is amplified by the low-noise amplifiers. The amplified signals are converted into 1 bit digital data by the comparators. In this paper, to evaluate the effect of clock offset with TDOA, a system with two Rx antennas is assumed. Fig. 2 shows the block diagram of the receiver with the proposed two-stage averaging scheme.
2.1 Transmitted signal

A monocycle pulse transmitted in the IR-UWB ranging system is expressed as

\[
\omega(t) = \left(1 - 4\pi \left(\frac{t}{\tau_m}\right)^2\right) \exp\left(-2\pi \left(\frac{t}{\tau_m}\right)^2\right) \quad (1)
\]

where \( \tau_m \) is the pulse duration \([8, 9]\). The pulse duration is defined as the time range including 99% of the signal power \([10]\). Fig. 3 shows the monocycle pulse assumed in this research. From \([6]\), the pulse duration is about 4 ns and the pulse interval is about 200 ns.

2.2 Comparator and pulse averaging

Fig. 4 shows the process of pulse averaging. The comparator converts the received signal into 1 bit digital samples, \( 0, 1 \). These converted digital samples, \( r_d(x) \), are defined as

\[
r_d(x) = \begin{cases} 
1, & r(xT_s) > 0 \\
0, & \text{otherwise}
\end{cases} \quad (2)
\]

where \( r \) is the received signal and \( T_s \) is the sampling interval.

These digitised samples are put into the pulse averaging block. The digitised samples are averaged over multiple frames in order to reduce the noise power. The 4th averaged sample in one frame of the \( i \)th output from the averaging block, \( r_p(i,k) \), is expressed as

\[
r_p(i,k) = \frac{1}{N_p} \sum_{j=0}^{N_p-1} r_d(N_f N_i j + N_f j + k) \quad (3)
\]

where \( N_p \) is the number of pulse averaging, \( N_f \) is the number of samples in one frame.

2.3 Timing detection and TDOA averaging

Fig. 5 shows the process of timing detection. The output of the pulse averaging process is converted from \([0, 1]\) to \([-1, 1]\), and its absolute value is taken. Next, the converted signal is correlated with the rectangular template signal. The \( k \)th correlation sample in the frame of the \( i \)th output, \( r_c(i,k) \), is given as

\[
r_c(i,k) = \sum_{l=0}^{N_f-1} [2 \times r_t(l) - 0.5] \times r_c(i,k) \quad (4)
\]

where \( r_t(l) \) is the template signal. When the correlation value exceeds the threshold, \( T_h \), the pulse timing, \( k_i \), is detected as the \( i \)th pulse timing

\[
r_c(i,k_i) > T_h \quad (5)
\]
is calculated in each Rx antenna, and the $i$th TDOA, $\Delta_i$, is obtained. The averaged value of the TDOA, $\hat{\Delta}$, is expressed as

$$\hat{\Delta} = \frac{\sum_{i=0}^{N_t-1} \Delta_i}{N_t} \quad (6)$$

where $N_t$ is the number of the TDOA averaging.

### 2.4 Clock offset

Each receiver has different clock time, $t_c$. Clock time can be expressed as a function of the true time, $t$, as follows

$$t_c = C(t) \quad (7)$$

In this paper, $C(t)$ is defined as

$$C(t) \approx X t + Y \quad (8)$$

The clock offset is a lag between the clock time and the true time, and it is given as

$$t_c - t = (X - 1)t + Y \quad (9)$$

where $Y$ is the initial gap of the phase between the transmitter and the receiver, and $X - 1$ depends on the performance of the clock. Here the clock offset is assumed as $\pm 40$ ppm [11]. In this system, the total clock offset is $\pm 80$ ppm because there are two clocks in the transmitter and the receiver.

The accuracy of the frame interval is lost due to the effect of the clock offset. It can be negligible in one frame because the timing gap is very small. However, this small gap is accumulated, and it shifts the timing of the received pulse by one sample during the multiple frames. Therefore if the averaging period of the received pulse signal is long, it may lose signal energy due to the timing shift as shown in Fig. 6.

In this paper, the clock offset is assumed to be $X - 1$, and $Y$ is given with uniform distribution over one frame duration.

### 3 Numerical results

#### 3.1 Simulation conditions

Simulation conditions are shown in Table 1. The total number of averaging is 1200 and the number of TDOA averaging is set to the total number of averaging per number of pulse averaging. The pulse duration of the transmitted signal is 4 ns, the pulse interval is 200 ns, the SNR is 0 dB, the clock offset is (40, 80) ppm, and the initial value of the clock offset follows uniform distribution between $[-0.5, 0.5]$ ns. The threshold for pulse detection is ranged from 0.1 to 1, and correlation value is normalised by the maximum possible output of the correlator. The number of trial is 1000 for each plot.

When the peak of the correlation value falls due to the clock offset, the pulse might not be detected by setting high threshold. This case is regarded as ‘no pulse detection’. If the pulse is detected, the mean-squared error (MSE) of TDOA between Rx 1 and Rx 2, $T_{12}$, is calculated as

$$\text{MSE} = \frac{1}{N} \sum_{i=1}^{N} (T_{12i} - \hat{T}_{12})^2 \quad (10)$$

where $\hat{T}_{12}$ is the true value of TDOA between Rx 1 and Rx 2.

#### Table 1 Simulation conditions

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<th>trial</th>
<th>10 000/plot</th>
</tr>
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<tr>
<td>pulse type</td>
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<td>pulse duration</td>
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</tr>
<tr>
<td>pulse interval</td>
<td>200 ns</td>
</tr>
<tr>
<td>template signal type</td>
<td>rectangler pulse</td>
</tr>
<tr>
<td>template signal duration</td>
<td>4 ns</td>
</tr>
<tr>
<td>total number of averaging</td>
<td>1200</td>
</tr>
<tr>
<td>number of pulse averaging</td>
<td>10, 15, 20, 25, 30, 40, 50, 60, 75, 80, 100, 120, 150, 200</td>
</tr>
<tr>
<td>number of TDOA averaging</td>
<td>(total averaging)/(pulse averaging)</td>
</tr>
<tr>
<td>clock offset (X-1)</td>
<td>80, 40 ppm</td>
</tr>
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<td>initial value (Y)</td>
<td>uniform distribution $[-0.5, 0.5]$ ns</td>
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</tr>
<tr>
<td>$T_{12}$</td>
<td>10 ns</td>
</tr>
</tbody>
</table>

![Figure 6 Influence of clock offset for averaging](image-url)
3.2 Probability of no pulse detection

The probability of no pulse detection against the normalised threshold is shown in Figs. 7 and 8 with the clock offset of 40 and 80 ppm.

When the clock offset decreases, the probability of no pulse detection reduces. The probability of timing shift is small even with a large clock offset. However, the reduction of the peak output of the averaged signal mainly depends on the phase of timing shift during the averaging process. If the timing shift happens at the beginning or at the end of the averaging process, most of the pulses are averaged with the corresponding samples of the frame and the peak output is large. On the other hand, if the timing shift occurs in the middle of the averaging, the energy of the pulse signal is divided into two timing slots and the peak output reduces.

However, if the number of pulse averaging or the amount of clock offset is large, the timing shift might happen more than once during pulse averaging. For example, when the number of pulse averaging is 200 and the clock offset is 80 ppm, the timing shift occurs three or four times, and when the clock offset is 40 ppm, it occurs only once or twice. Therefore Figs. 7 and 8 show different probability with the same normalised threshold. Moreover, if the number of pulse averaging is small, the probability of no pulse detection decreases.

From the above mentioned, as the threshold decreases and the number of pulse averaging reduces, the receiver is more robust to the clock offset from the view point of no pulse detection probability.

3.3 Mean-squared error

The MSE performance against the normalised threshold is shown in Figs. 9 and 10 with the clock offset of 40 and 80 ppm.

It is clear from these figures that the clock offset does not change the MSE significantly. When the number of pulse

![Figure 7](image1.png) **Figure 7** Probability of no pulse detection against normalised threshold (SNR: 0 dB, clock offset: 80 ppm)

![Figure 8](image2.png) **Figure 8** Probability of no pulse detection against normalised threshold (SNR: 0 dB, clock offset: 40 ppm)

![Figure 9](image3.png) **Figure 9** MSE against normalised threshold (SNR: 0 dB, clock offset: 80 ppm)

![Figure 10](image4.png) **Figure 10** MSE against normalised threshold (SNR: 0 dB, clock offset: 40 ppm)
averaging grows, the threshold for the same MSE of less than 100 ns$^2$ decreases. It is because the noise power reduces with the number of pulse averaging. Therefore the number of pulse averaging and the threshold should be increased from the viewpoint of the MSE.

The MSE settles to 100 ns$^2$ with a small threshold. This is because the correlation output exceeds the threshold even though the pulse signal does not exist as shown in Fig. 11. In this case, the first sample is recognised as the pulse timing. $T_{12}$ is 10 ns, and then MSE becomes 100 ns$^2$. As the threshold grows, the MSE also increases and reaches the peak at a different value of the threshold for each number of pulse averaging. In this case the correlation value then sometimes exceeds the threshold as shown in Fig. 12 and the detected pulse timings are not stable.

### 3.4 Number of pulse averaging

Figs. 13 and 14 show the probability of no pulse detection and the MSE against the number of pulse averaging when the SNR is 0 dB and the clock offset is 80 ppm. These figures are redrawn with the same plots in Figs. 7 and 9 over the different axes.

It is clear that the probability of no pulse detection and the MSE are the trade-off between the threshold and the number of pulse averaging. Therefore it is necessary to select the appropriate threshold and the suitable number of pulse averaging according to the required performance.

### 4 Conclusions

In this paper, the effect of the clock offset on the accuracy of the IR-UWB ranging system with comparators has been presented. The two-stage averaging scheme for the ranging system has also been proposed. The clock offset causes the timing shift during the averaging process and reduces the pulse energy. As a result, the probability of no pulse detection and the MSE are the trade-off between the
threshold and the number of pulse averaging. It is necessary to select the threshold and the number of pulse averaging according to the required performance.

5 References


