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RF TOF Measurement using M-Sequential Coded Vernier Effect by Interleaved Correlation Technique

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Abstract: In this report, we propose a novel RF TOF ranging method using M-sequence code with heterogeneous clock system for wireless sensor network. Since this method makes new time resolution which is smaller than the intrinsic time resolution of two clocks, it is theoretically possible to get RF signals more precisely at receiver. RF TOF between two sensor nodes is obtained by calculating the cross-correlation function between reference and received signal, and detecting its peak. Our research made it clear that the new TOF measurement method improve accuracy of measurement in the presence of noise as compared with our conventional method. In addition, some simulation results shows that TOF measurements of the proposed method using ASK modulation are less affected by band-limitation.

Keywords: wireless sensor networks (WSNs), time-of-flight (TOF), Vernier effect, M-sequence, correlation

1. INTRODUCTION

For wireless sensor networks (WSNs), localization of sensor nodes with high precision is required. RF Time-of-Flight (TOF) measurement with high frequency clocks can fulfill the requirement, and it has an advantage in using available communication hardware in the RF sensor nodes [1]. On the other hand, high frequency clock system causes high power consumption and makes the sensor nodes expensive.

To deal with this issue, an RF TOF measurement system has been proposed, which using new signal processing method based on Vernier effect with two heterogeneous clocks [2]. It was represented that iterative execution of RF impulse and sensing using two heterogeneous clocks of which the ratio is N to M generates new virtual time resolution $\Delta = \frac{T_a}{N} = \frac{T_b}{M}$ (N and M are coprime). Additionally, it was shown that RF TOF can be estimated using the particular sensing patterns according to the size of RF TOF, which is classified into the integral multiple of Δ [3].

Under the real environmental condition, there are the two major problems with these methods. First, the TOF measurement system is unable to work if sensing patterns have even one bit error. Second, since the RF impulse signal has wide bandwidth characteristics, we just have to use band-limited signal which may reduce the accuracy of the measurement. Here, we propose a novel RF TOF measurement system which utilize the periodicity and auto-correlation function property of PN (Pseudo-random Noise) code, such as M-sequence code, based on Vernier effect.

2. M-SEQUENTIAL CODED VERNIER EFFECT

In this report, M-sequence code is used to measure range. We propose the TOF measurement system as illustrated in Fig. 1. The system notation is shown in Table 1. The ratio of two heterogeneous clocks is

$$T_a : T_b = N : M, \tag{1}$$

where N and M are coprime.

Node A, which operates as a transmitter, sends one chip of M-sequence code every T_a seconds. M cycles of M-sequence code is transmitted from node A in total. Node B, which operates as a receiver, samples propagated RF signal every T_b seconds.

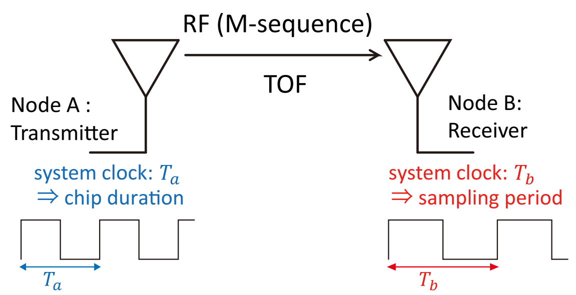

Fig. 1 TOF measurement system with heterogeneous clocks ($T_a : T_b = N : M$)

Table 1 System design notation

notation	item
n	order of M-sequence
T_a	chip duration of M-sequence
T_b	sampling period

The state of sampling, from the first cycle to the third cycle of M-sequence, are shown in Fig. 2 (a). Due to limitations of space, the rest of signals are not depicted. For purposes of illustration, these received signals are separated into three parts, but they are actually continuous.

T is the cycle length of M-sequence, which is represented by Eq. (2).

$$T = (2^n - 1)T_a \tag{2}$$

† Sho Yoshida is the presenter of this paper.

Since we utilize two heterogeneous clocks, T_a and T_b, the sampling points are shifted bit by bit in each cycle (Fig. 2 (a)). This property is analogy of equivalent time sampling mode of a digital oscilloscope [4]. In Fig. 2 (b), the samples from the three cycles are interleaved. Hence, node B can get propagated M-sequence code by finer resolution.

The improved resolution is represented by the following formula Eq. (3).

$$\Delta = \frac{T_a}{N} = \frac{T_b}{M} \tag{3}$$

Therefore, this RF TOF ranging method have the same Vernier effect as our conventional system. We call the property of the proposed method "M-Sequential Coded Vernier Effect".

After the sampling, the received signals are interleaved in the appropriate order, and are correlated with the reference signal. We call this proceeding "Interleaved Correlation Technique". Since we use M-sequence code as a transmission signal, moreover, we can detect the peak of cross-correlation function with ease, to estimate TOF.

This reconstruction is performed on the basis of the following rule. Here, t is the real-time sampling points and t' ($0 \leq t' < T$) is the equivalent-time sampling points. The rule of interleaving is described by the following relational expression, Eq. (4).

$$t' = \mathrm{mod}[t, T] \tag{4}$$

$\mathrm{mod}[x, y]$ expresses the remainder of dividing x by y. An example of interleaving based on Eq. (4) is shown in Fig. 3 (a), (b).

However, the resolution does not satisfy Eq. (3) if the measurement system using some undesirable combinations of two clocks. The condition is represented by Eq. (5).

$$k \times (2^n - 1)T_a = l \times T_b \tag{5}$$

k is the positive integer such that $k < M$, and l is any positive integer. Since the shift of sampling points does not happen under Eq. (5), the resolution of TOF measurements is not improved.

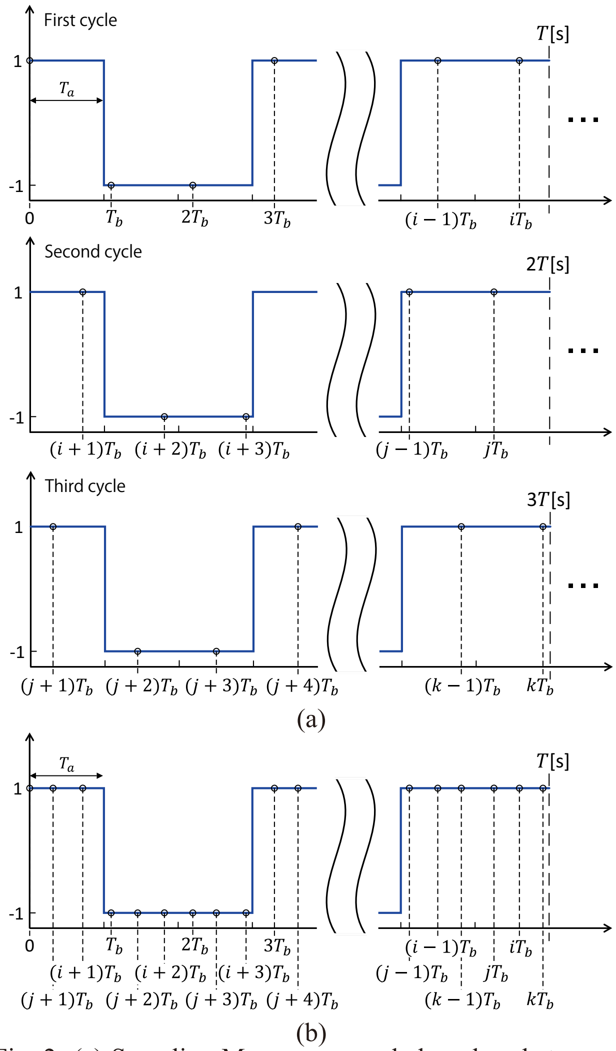

Fig. 2 (a) Sampling M-sequence code based on heterogeneous clock system (b) M-sequence code reconstructed by Eq. (4)

3. SIMULATION AND RESULTS

3.1. The resolution improvement by proposed method

Our new method is simulated under the following conditions; $n = 3$, $T_a = 1.0\,\mu$s, $T_b = 1.1\,\mu$s

RF TOF measurement resolution Δ is represented by Eq. (6), (7).

$$T_a : T_b = N : M = 10 : 11 \tag{6}$$

$$\Delta = \frac{T_a}{N} = \frac{1.0}{10} = 0.1\,\mu\text{s} \tag{7}$$

The calculation results of cross-correlation between reference signal (TOF = 0 s) and received signal (TOF = 1.6, 1.7 μs) are shown in Fig. 4. Two peaks of the cross-correlation function in Fig. 4 are able to be distinguished.

For comparison, the cross-correlation function obtained by the measurement system using the same clock ($T_a = T_b = 1.0\,\mu$s) is shown in Fig. 5. The two peaks could not be distinguished because the resolution, Δ, is the same as sampling period, T_b.

As a result, the new virtual time resolution, $\Delta = 0.1\,\mu$s is generated by our proposed method.

3.2. Relationship between BER and TOF measurement

Since cross-correlation function is used to measure TOF, it is expected that the new method improve accuracy of measurement in the presence of noise as compared with our conventional method. The TOF measurement using received signals (bits) which have bit error due to noise should be simulated. Here, Bit Error Rate (BER) is defined as Eq. (8).

$$\mathrm{BER} = \frac{\text{number of erroneous bits}}{\text{total number of received bits}} \times 100 \tag{8}$$

The simulation is performed 100 times to examine the success rate. If the calculated value of TOF is in agree-

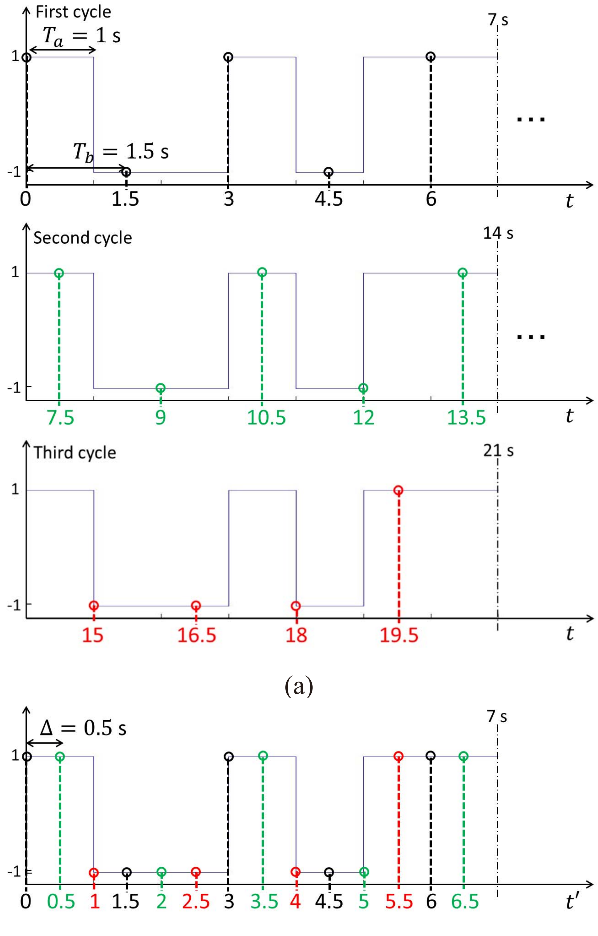

Fig. 3 (a) Sampling M-sequence code based on heterogeneous clock system ($n = 3$, $T_a : T_b = 2 : 3$) (b) Reconstructed M-sequence code

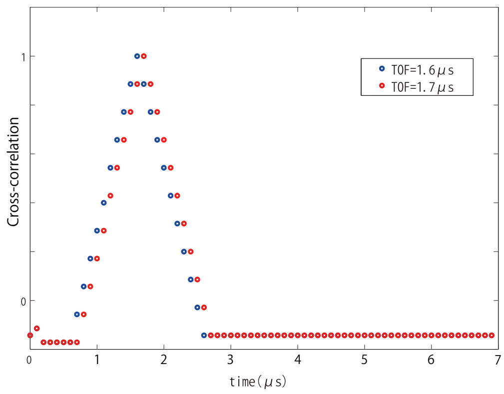

Fig. 4 Cross-correlation function obtained by TOF measurement system with the two heterogeneous clocks ($T_a : T_b = 10 : 11$)

ment with the theoretical value of TOF completely, the measurement is considered success.

The results are shown in Fig. 6. If BER is within several percent, the measurement will be successful in more than 70 percent of the probability without theoretical value of TOF. Considering that our conventional TOF

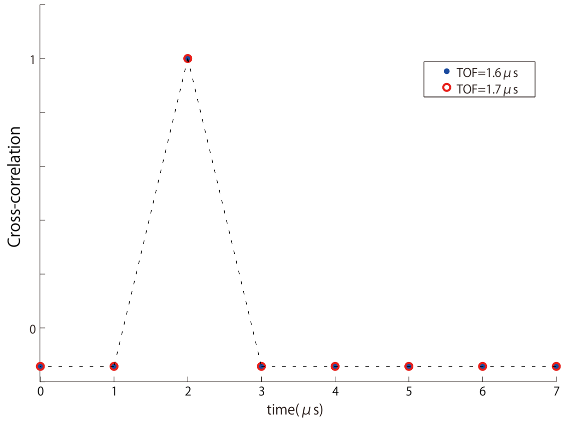

Fig. 5 Cross-correlation function obtained by TOF measurement system with the same two clocks

measurement will be failure if sensing patterns have even one bit error, it is thought that the proposed method is more robust ranging.

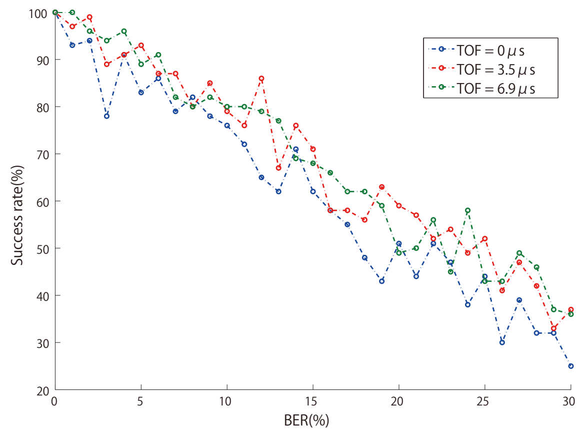

Fig. 6 Success rate of proposed TOF measurement under the noisy environment

3.3. ASK modulation and band-limitation

RF modulation and band-limitation should be considered when WSNs are operated in actual environment. In this work, therefore, ASK modulation and envelope demodulation is usd for our measurement system because these processes are simple and could be easily used in combination with M-Sequential Coded Vernier Effect. In additon, roll-off filtered M-sequence code is applied to baseband signal in order to using band-limited signal in RF communication systems, such as WSNs.

An Impulse response of a roll-off filter is represented by Eq. (9).

$$h_{ROF}[k] = \frac{\sin(\pi k T'_R/T_R)}{\pi k T'_R/T_R} \cdot \frac{\cos(\alpha_F \pi k T'_R/T_R)}{1-(2\alpha_F k T'_R/T_R)^2} \qquad (9)$$

T_R is transmission interval, i.e. chip duration of M-sequence, T_a. α_F is roll-off rate ($0 \leq \alpha_F < 1$), and T_R/T'_R is oversampling rate. For example, third-order M-sequence code filtered by the roll-off filter ($T_R = T_a = 125$ ns, $T_R/T'_R = 20$, $\alpha_F = 0.1$) is illustrated in Fig. 7. In this case, the bandwidth of the modulated

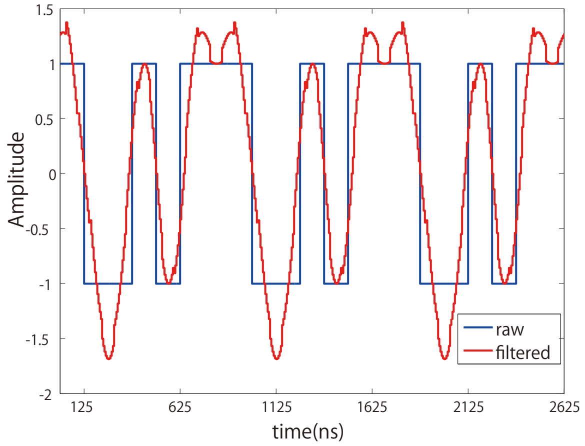

Fig. 7 Band-limited M-sequence code by roll-off filter

signal is limited to $\frac{1}{T_R} = 8\,\mathrm{MHz}$.

Here, our method using ASK modulation is simulated under the following conditions; $n = 3$, $T_a = 125\,\mathrm{ns}$, $T_b = 40\,\mathrm{ns}$. Roll-off filtered M-sequence code shown in Fig. 7 is used to measurement simulation to consider the band-limitaiton. The expected resolution Δ is represented by Eq. (10), (11).

$$T_a : T_b = N : M = 25 : 8 \tag{10}$$

$$\Delta = \frac{T_a}{N} = \frac{125}{25} = 5\,\mathrm{ns} \tag{11}$$

The simulation results are indicated in Table 2. We

Table 2 Simulation results (Band-limitation)

theoretical TOF (t_f)	measured TOF
$0 \leq t_f < 3\,\mathrm{ns}$	0 ns
$3 \leq t_f < 8\,\mathrm{ns}$	5 ns
$8 \leq t_f < 13\,\mathrm{ns}$	10 ns
$13 \leq t_f < 18\,\mathrm{ns}$	15 ns
$18 \leq t_f < 23\,\mathrm{ns}$	20 ns
$23 \leq t_f < 28\,\mathrm{ns}$	25 ns
$28 \leq t_f < 33\,\mathrm{ns}$	30 ns
$33 \leq t_f < 38\,\mathrm{ns}$	35 ns
$38 \leq t_f \leq 40\,\mathrm{ns}$	40 ns

could confirm that the new virtual time resolution, $\Delta = 5\,\mathrm{ns}$ is generated by the proposed method with ASK modulation and band-limitation.

One of the results of cross-correlation function between reference signal (TOF = 0 s) and received signal (TOF = 35 ns) are shown in Fig. 8. The shape of the function calculated by filterd signal is broadened but the peak arrival time is the same as raw. TOF measurements of our new method using ASK modulation are less affected by band-limitation.

4. CONCLUSION

In this paper, we propose a novel RF TOF measurement system which utilize the periodicity and auto-correlation function property of M-sequence code based

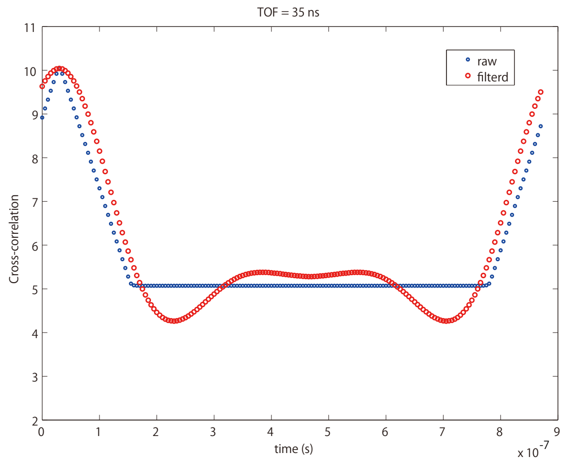

Fig. 8 Cross-correlation function with band-limitated signals (TOF = 35 ns)

on Vernier effect. This scheme uses sending and receiving M-sequence code at the TOF measurement system using two heterogeneous clocks and the simple signal processings, permutation and calculation of cross-correlation. Since our method generates new virtual time resolution which is smaller than the intrinsic time resolution of two clocks, localization of sensor nodes with high precision and low energy consumption could be achieved. Relationship between TOF measurement and BER, ASK modulation, and band-limitation has been studied and simulated to apply our method to WSNs in the real environmental condition.

5. FUTURE STUDIES

We have to examine three items as follows;

- Implementation of the proposed method
- Making RF devices and developping TOF measurement system to test ranging in the real environment
- Study of optimal RF modulation for the method

REFERENCES

[1] Steven Lanzisera, DavidT.Lin and Kristofer S.J.Pister, "RF Time of Flight Ranging for Wireless Sensor Network Localization" Proc. International Workshop on Intelligent Solutions in Embedded Systems 2006, pp.1-12, (2006)

[2] Sang-il Ko, Jun-ya Takayama and Shinji Ohyama, "A Novel RF Symmetric Double Sided Two Way Range Finder based on Vernier Effect" ICCAS 2008, pp.1802-1807, (2008)

[3] J. Takayama, S. I. Ko and S. Ohyama, "Generalized Vernier Effect and Its Application for RF Propagation Time Measurement" Transaction of SICE, 47-12, 597/605 (2011-12)

[4] Vladica Sark, Eckhard Grass, "Modified Equivalent Time Sampling for Improving Precision of Time-of-Flight Based Localization" PIMRC 2013, 370 - 374, (2013-9)