Hardware Evaluations of Simple Radio Positioning System Based on Direct Sequence Spread Spectrum

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ABSTRACT

This paper proposes a simple positioning scheme without huge computational cost. The proposed scheme employs a three-element loop array for the transmitter. A Direct-Sequence Spread Spectrum (DS/SS) sequence is transmitted at a frequency of Low Frequency (LF) band. We evaluate location determination error rate by using a computer simulator and theoretical analysis. The theoretical analysis agrees with the simulation result. The difference is at most 1.3 dB at error rate of 10^{-5}. Computer simulation result shows that the proposed technique can identify the region of 2 by 3 meters at the region determination error rate of 10^{-2}. In order to show the hardware complexity requirement for implementing the proposed receiver, the impact of bit width for ADC (Analog-to-Digital Converter), and digital signal processing block to the error rate performance is evaluated by computer simulation. Computer simulation shows that the proposed scheme can be constructed by 2-bit ADC and 5-bit integrate and dump filter.

Keywords: Extended M-sequence, Loop antenna arrays, Magnetic fields, Correlation, Region identification

1. INTRODUCTION

Location-aware systems attract much attention in the fields of wireless technologies and mobile computing. One of the most famous applications using location information is car navigation system. It gives a drive route to a destination using GPS (Global Positioning System). GPS is the de facto standard technique of position detection in this way. We need to choose a optimum technique considering various factors: detection accuracy, complexity of detection device, disaster tolerance, and detection coverage, for indoor services using location information. Position detection techniques use RSS (Received Signal Strength), TOA (Time of Arrival), TDOA (Time Difference of Arrival), or AOA (Angle of Arrival) [1]. Position detection techniques based on RSS use signal's distance attenuation from a target. We need at least 3 nodes and a model of the distance attenuation to calculate the target position. Position detection techniques based on TOA and TDOA use a signal propagation time. We need at least 3 nodes and accurate time synchronization between nodes to calculate the target position. In AOA, the nodes measure the angle of the sound or radio wave from a target. We need directional microphone, antennas, or array antenna to calculate the target position.

Many indoor location aware systems were proposed by using GPS technique, RFID (Radio Frequency identification), cellular, UWB (Ultra Wide Band), wireless LAN (Local Area Network), and bluetooth [2]. Most of their position detection systems using radio commonly measure wireless environment and estimate a target position by signal power or arrival time. Most of the studies have been carried out to detect the accurate position of an object. The user uses processed data about a location by the coordinate position information in the case of actual services.

Keyless entry system is one of the objectives of this paper. The key detects its location and changes the behavior for keyless entry systems. For example, it can lock and unlock doors when the key is outside of the car. It starts up the engine if it is in the car. In this case the key only to determine whether it is in the car or not. There are several applications which only require the region identification of an object [3]. Ogawa's group proposed a region identification scheme [4] that measured distances between target and base stations based on RSS by LS (Least Square) and mapped them into the position. Although the proposed scheme is efficient for position identification, it requires huge computational cost. Since the power consumption for smart key is strictly limited, position identification scheme based on the LS algorithm is not suitable for our purposes. We propose a low cost simple radio positioning system based on DS/SS for keyless entry systems.

The authors have proposed simple radio positioning system based on DS/SS techniques [5–9]. The

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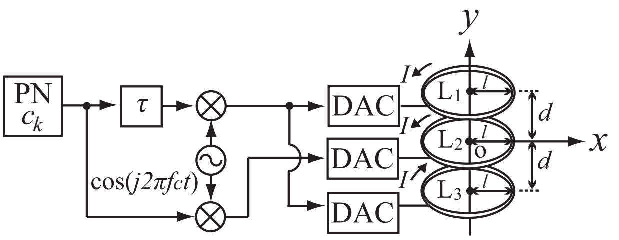

Fig.1: *Block diagram of the transmitter*

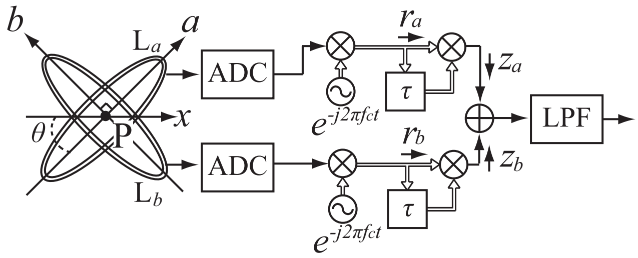

Fig.2: *Block diagram of the receiver*

proposed transmitter is composed of three antennas. Two out of three antennas are used for generating the magnetic field for representing the target region and the remaining antenna is used for transmitting the reference signal [10], [11]. The pseudo-random noise (PN) sequence is applied to the antenna element L_2 as reference signals. The same PN sequence is delayed and transmitted from two antenna elements L_1 and L_3. At the receiver side, the region can be determined by comparing the phase difference between the PN sequence and its delayed version.

We have evaluated a region where the receiver can detect its position, and theoretically derive a detection error rate. In order to implement the proposed receiver, the impact of hardware requirements such as bit resolution for ADC and digital signal processing blocks to the error rate performance should be evaluated. For example, a SAR (successive approximation register)-type ADC needs n times comparison when the bit resolution is n bits. The computational cost for the digital signal processing circuit followed by the ADC depends upon the bit resolution of the ADC. In this paper, the required bit width for the ADC and LPF (low-pass filter) is evaluated by computer simulation.

The remainder of this paper is organized as follows. Section 2 introduces the compositions of the transmitter and receiver for a region identification system based on DS/SS signals. It is followed by the relationship between density of magnetic fluxes at the receiver and value after signal processing in section 3. Section 4 presents mathematical model of the proposed receiver. We derive the error rate of the proposed technique using analysis models in section 5. Section 6 presents the simulation results and reveals performances of the proposed system. Section 7 shows the relationship between the ADC bit resolution and region determination error rate performance. Finally section 8 concludes this paper.

2. SYSTEM MODEL

Now, let us introduce the system model of the proposed region identification system.

The transmitter model is shown in Fig. 1. The transmitter consists of three circular-loop antennas with common center, which is denoted as y-axis, and the same radius l. Distances between antennas are uniform and given by d. Transmit signals are made by sine wave of central frequency f_c and c_k which is an orthogonal M-sequence whose chip length is N. Transmit signals in baseband expression $u(t)$ and frequency band expression $s_0(t)$ are shown as follows.

$$u(t) = \sum_{k=-\infty}^{\infty} c_k f(t - kT_c) \tag{1}$$

$$s_0(t) = \mathrm{Re}\left[\exp\left(j2\pi f_c t\right) u(t)\right] \tag{2}$$

where T_c is chip duration, $\mathrm{Re}[\boldsymbol{z}]$ denotes the real part of $\boldsymbol{z}$, and

$$f(t) = \begin{cases} 1; & |t| < T_c/2 \\ 0; & \text{otherwise} \end{cases}$$

is a pulse wave. Transmit signals are converted by DAC (Digital-to-Analog Converter) and sent by antennas. L_1 and L_3 antennas bind L_2 and transmit signals modulated by $c_{k-\tau}$ which is made of spread signal delayed τ. Delayed transmit signals are shown as follows [12].

$$s_D(t) = \mathrm{Re}\left[\exp\left(j2\pi f_c t\right) u(t - \tau T_c)\right] \tag{3}$$

Note that the direction of the current in antennas L_1 and L_3 are opposite. Due to the opposite direction of the current in L_1 and L_3, positive (negative) magnetic flux can be detected in both regions of $y > 0$ and $y < 0$. On the other hand, the magnetic flux from L_2 has a direction according to the current flowing through L_2. Thus, it might be possible to identify the receiver's existing region by the pair of received magnetic flux from the antennas. We define x-axis as a direction to a part of antenna L_2 from the center. x-axis and y-axis cross each other at right angle. We assume that the plane spanned by x-axis and z-axis is the boundary of two regions, that is, the transmitter is located at the boundary. Either one of the regions where $y \geq 0$ is called the front-side region and the remaining region is the back-side region. Our objective is to detect the region where a receiver exists from the two regions.

The hardware complexity and power consumption of the receiver is strictly limited. On the other hand, the conventional keyless entry system uses several miniature antennas in a key. In this paper, we adopt the two-antenna system similar to that in [13].

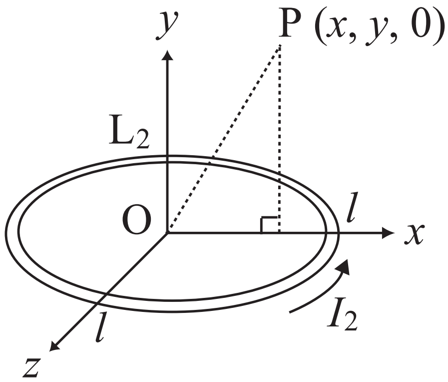

Fig.3: *Geometry of a circular-loop antenna*

The block diagram of the receiver is shown in Fig. 2. Signals received by the two antennas are converted to digital signals by ADC, multiplied by $\exp(-j2\pi f_c t)$ and transformed to baseband signals. We use these orthogonal antennas which receive signals with its center at the point P. An angle between x-axis and a-axis of antenna L_a is defined as θ. Received signals at antenna L_a and L_b are given as $r_a(t)$ and $r_b(t)$, respectively. We calculate correlation between $r_a(t)$, $r_b(t)$ and $r_a(t-\tau T_c)$, $r_b(t-\tau T_c)$, respectively. A decision variable is calculated by sum of their correlations through LPF. The receiver can identify its existing region using the sign of the decision variable. In this case, the receiver is implemented on a key in keyless entry system.

3. ANALYSIS OF MAGNETIC FIELD AND RECEIVED SIGNALS

The impact of bit width for ADC, and digital signal processing block to the error rate performance is evaluated by computer simulation. The bit error rate is derived theoretically. In the following, let us assume that L_1, L_2 and L_3 are antennas in the transmitter. L_2 is the central single loop antenna for reference. L_1 and L_3 are the two loop antennas used in combination for region determination. We will derive the received signals strength using the magnetic fields analysis.

3.1 Magnetic flux density by single loop antenna

Fig. 3 shows an alignment of a circular-loop antenna L_2. The current I_2 flows through the loop antenna of radius, l. Let us define a reception point P $(x, y, 0)$ as shown in Fig. 3. We analyze magnetic field vectors in $x-y$ plane at the point P. Magnetic flux density at P can be expressed according to Biot-Savart law as follows.

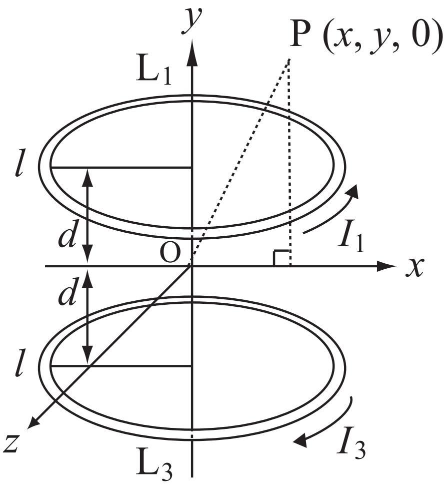

Fig.4: *Geometry of double circular-loop antennas*

$$B_{x1} = \frac{3\mu_0 I_2 l^2 xy}{4\left(x^2+y^2\right)^{\frac{5}{2}}} \tag{4}$$

$$B_{y1} = \frac{\mu_0 I_2 l^2\left(-x^2+2y^2\right)}{4\left(x^2+y^2\right)^{\frac{5}{2}}} \tag{5}$$

where μ_0 is the permeability in the free space.

3.2 Magnetic flux density by two loop antennas

Fig. 4 shows an alignment of two circular-loop antennas L_1 and L_3. We set two loop antennas in parallel with each other on the same central axis, and apply electrical current to two circular-loop antennas oppositely. Combined magnetic flux density from L_1 and L_3 is given similarly to (4) and (5) as follows.

$$B_{x2} = \frac{3\mu_0 I_1 l^2 x\left(y-d\right)}{4\left(x^2+\left(y-d\right)^2\right)^{\frac{5}{2}}} - \frac{3\mu_0 I_3 l^2 x\left(y+d\right)}{4\left(x^2+\left(y+d\right)^2\right)^{\frac{5}{2}}} \tag{6}$$

$$B_{y2} = \frac{\mu_0 I_1 l^2\left(-x^2+2\left(y-d\right)^2\right)}{4\left(x^2+\left(y-d\right)^2\right)^{\frac{5}{2}}} - \frac{\mu_0 I_3 l^2\left(-x^2+2\left(y+d\right)^2\right)}{4\left(x^2+\left(y+d\right)^2\right)^{\frac{5}{2}}} \tag{7}$$

3.3 Relationship between electromotive force and receiving antenna

Fig. 5 shows the alignment of the receiving circular-loop antennas. Because electromotive force is in proportion to magnetic flux density through the antenna, we can express V_a and V_b which are electromotive force derived from antenna L_a and antenna

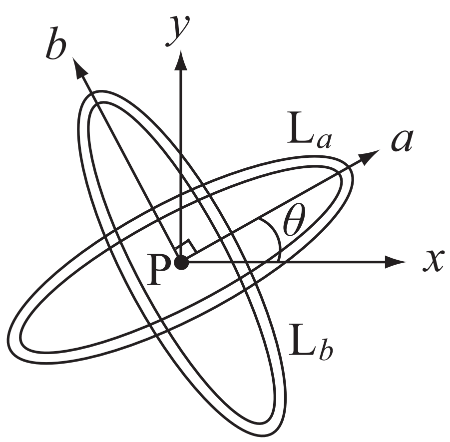

Fig.5: *Geometry of receiver antennas*

L_b.

$$V_a = k_1 \langle \mathbf{B}_1, \mathbf{a} \rangle + k_2 \langle \mathbf{B}_2, \mathbf{a} \rangle \quad (8)$$

$$V_b = k_1 \langle \mathbf{B}_1, \mathbf{b} \rangle + k_2 \langle \mathbf{B}_2, \mathbf{b} \rangle \quad (9)$$

where $\mathbf{a} = (-\sin\theta, \cos\theta)$ and $\mathbf{b} = (\cos\theta, \sin\theta)$ are normal vectors of a and b. $\mathbf{B}_1 = (B_{x1}, B_{y1})$ and $\mathbf{B}_2 = (B_{x2}, B_{y2})$ are vector expressions of magnetic flux densities influenced from the antenna L_2 and the combined antenna L_1 and L_3. $\langle \mathbf{B}_1, \mathbf{a} \rangle$ is the inner product of $\mathbf{B}_1$ and $\mathbf{a}$. Constants k_1 and k_2 are in proportion to the derivative of the current with respect to time and the largeness of the receive antenna.

3.4 Correlation function of received signals

The receiver calculates cross correlation z_a between the received signals $r_a(t)$ and that of the delayed signals $r_a(t-\tau T_c)$. The receiver receives DS/SS signals which are proportion to electromotive force (8) and are added noise n_a. $r_a(t)$ is given as follows.

$$r_a(t) = k_1 \langle \mathbf{B}_1, \mathbf{a} \rangle u(t) + k_2 \langle \mathbf{B}_2, \mathbf{a} \rangle u(t-\tau T_c) + n_a(t) \quad (10)$$

The correlation value z_a is given as follows.

$$\begin{aligned} z_a &= \frac{1}{T}\int_0^T r_a(t) r_a(t-\tau T_c) dt \\ &= \frac{1}{T}\int_0^T \Big((\langle \mathbf{B}_1, \mathbf{a} \rangle k_1)^2 u(t)u(t-\tau T_c) \\ &\quad + \langle \mathbf{B}_1, \mathbf{a} \rangle \langle \mathbf{B}_2, \mathbf{a} \rangle k_1 k_2 u(t) u(t-2\tau T_c) \\ &\quad + \langle \mathbf{B}_1, \mathbf{a} \rangle \langle \mathbf{B}_2, \mathbf{a} \rangle k_1 k_2 u^2(t-\tau T_c) \\ &\quad + (\langle \mathbf{B}_2, \mathbf{a} \rangle k_2)^2 u(t-\tau T_c) u(t-2\tau T_c) \\ &\quad + n_a(t) \big(\langle \mathbf{B}_1, \mathbf{a} \rangle k_1 u(t-\tau T_c) \\ &\quad + \langle \mathbf{B}_2, \mathbf{a} \rangle k_2 u(t-2\tau T_c) \big) \\ &\quad + n_a\big(t-\tau T_c\big) (\langle \mathbf{B}_1, \mathbf{a} \rangle k_1 u(t) \\ &\quad + \langle \mathbf{B}_2, \mathbf{a} \rangle k_2 u(t-\tau T_c) \big) \\ &\quad + n_a(t) n_a(t-\tau T_c) \Big) dt \end{aligned} \quad (11)$$

In this paper, we assume $\tau = \frac{T}{2}$. Thus, we have $u(t-2\tau T_c) = c(t)$, where $u(t)$ is the orthogonal M-sequence. Autocorrelation function of $u(t)$ is given as follows,

$$\begin{aligned} R(\tau) &= \frac{1}{T}\int_0^T u(t) u(t-\tau T_c) dt \\ &= \begin{cases} 1; & \tau = mN \\ 0; & \text{otherwise} \end{cases} \end{aligned} \quad (12)$$

where m is integer. No correlation between $u(t)$ and $u(t-\tau T_c)$ is desired. Using (12), correlation value can be simplified as

$$\begin{aligned} z_a &= 2 \langle \mathbf{B}_1, \mathbf{a} \rangle \langle \mathbf{B}_2, \mathbf{a} \rangle k_1 k_2 + \frac{1}{N} N_{a3} N_{a4} \\ &\quad - \frac{1}{N} (N_{a1} + N_{a2}) \big(\langle \mathbf{B}_1, \mathbf{a} \rangle k_1 + \langle \mathbf{B}_2, \mathbf{a} \rangle k_2 \big), \end{aligned} \quad (13)$$

where N_{an} $(n = 1, 2, 3, 4)$ and N_{bn} are noise components whose variance is $\frac{N_0 T}{2}$. Similarly, z_b is given as follows.

$$\begin{aligned} z_b &= 2 \langle \mathbf{B}_1, \mathbf{b} \rangle \langle \mathbf{B}_2, \mathbf{b} \rangle k_1 k_2 + \frac{1}{N} N_{b3} N_{b4} \\ &\quad - \frac{1}{N} (N_{b1} + N_{b2}) \big(\langle \mathbf{B}_1, \mathbf{b} \rangle k_1 + \langle \mathbf{B}_2, \mathbf{b} \rangle k_2 \big) \end{aligned} \quad (14)$$

Consequently, the decision variable $z_d = z_a + z_b$ can be obtained by (13) and (14). A direction of magnetic flux densities influenced from combined antenna L_1 and L_3 is expected to be in the same direction as a direction of magnetic flux densities influenced from antenna L_2 in $y \geq 0$. On the other hand, a direction of magnetic flux densities influenced from combined antenna L_1 and L_3 is expected to be in the opposite direction to a direction of magnetic flux densities influenced from antenna L_2 in $y \leq 0$. Therefore, it is possible to identify the receiver's existing region whether $y \geq 0$ or $y \leq 0$ by checking the sign of z_d.

4. MATHEMATICAL MODEL OF PROPOSED RECEIVER

For simplicity, we assume that transmit signals are not modulated by additional information. Baseband signals are given by

$$r(t) = h_0 u(t) + h_1 u(t-\tau T_c) + z(t), \quad (15)$$

where $h_i (i = 0, 1)$ represents the attenuation of directed signals and delayed signals from L_2 and the pair of antennas. Furthermore, $z(t)$ is an additive white Gaussian noise (AWGN) component. We can rewrite the received signals as

$$r_k = h_0 c_k + h_1 c_{k+\tau} + z_k \quad (16)$$

where $c_k = c(kT_b), r_k = r(kT_b)$, and $\tau = \frac{N}{2}$. $z_k = z(kT_b)$ is AWGN component after sampling.

The received signals are then applied to the differential demodulator. The output of the demodulator is given by

$$u_k = \mathrm{Re}\left[r_k r_{k+\tau}^*\right] \tag{17}$$

A decision variable is calculated by the output u_k

$$y = \sum_{k=0}^{N-1} u_k. \tag{18}$$

We can determine the receiver's region whether y is negative or positive.

5. ERROR RATE ANALYSIS

In this section, we theoretically derive the error rate. Let us suppose that the received signals are represented in vector form as:

$$\mathbf{r_k} = [r_k, r_{\tau+k}, r_{N+k}]^T. \tag{19}$$

Received signals vector is given by:

$$\mathbf{r_k} = h_0 \begin{pmatrix} c_k \\ c_{\tau+k} \\ c_k \end{pmatrix} + h_1 \begin{pmatrix} c_{\tau+k} \\ c_k \\ c_{\tau+k} \end{pmatrix} + \mathbf{z} \tag{20}$$

The covariance matrix of $\mathbf{r}$ is given by

$$\mathbf{R} = \frac{1}{2} E\left[\mathbf{r}_k^* \mathbf{r}_k^T\right] \quad = [\rho_{ik}]_{i,k=0,1,2} \tag{21}$$

where the i-th row, the k-th column element is given by

$$\rho_{ik} = \begin{cases} \sigma^2 & (i = k) \\ 0 & (i \neq k) \end{cases} \tag{22}$$

Then, the decision variable can be expressed in quadric form as:

$$u_k = \mathbf{r}_k^H \mathbf{F} \mathbf{r}_k, \tag{23}$$

where

$$\mathbf{F} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \tag{24}$$

is a matrix, which represents the demodulator.

Now we can derive the pairwise error probability. Suppose that the probability density function of $X = u_k$ is defined as $p(X)$, and

$$\begin{aligned} G(\xi) &= \int_{-\infty}^{\infty} p(x) \mathrm{e}^{j\xi X} dX \\ &= \frac{\exp\left\{-\frac{\langle \mathbf{r} \rangle^{T*}}{2} (\mathbf{R}^*) \left[\mathbf{I} - (\mathbf{I} - \mathbf{2j}\xi \mathbf{R}^* \mathbf{F})^{-1}\right] \langle \mathbf{r} \rangle\right\}}{\det(\mathbf{I} - \mathbf{2j}\xi \mathbf{R}^* \mathbf{F})} \end{aligned} \tag{25}$$

is its characteristic function. The characteristic function is further rewritten as

$$G(\xi) = \frac{\exp\left[\frac{-12\xi^2\sigma^2|\overline{r_0}|^2 + 4j\xi \mathrm{Re}[\overline{r_0}^* \overline{r_\tau}]}{1+8\xi^2\sigma^4}\right]}{1 + 8\xi^2\sigma^4}. \tag{26}$$

The r-th moment of X is calculated by the r-th derivative of the characteristic function.

$$E[X^r] = (-i)^r \left.\frac{\mathrm{d}^r G(\xi)}{\mathrm{d}\xi^r}\right|_{\xi=0} \tag{27}$$

Substituting (26) into (27), we can derive the mean and variance of y as $4\mathrm{Re}\left[\overline{r_0}^* \overline{r_\tau}\right]$ and $24\sigma^2 \left|\overline{r_0}\right|^2 + 16\sigma^4$ respectively. The decision variable is given by

$$y = \sum_{k=0}^{N-1} u_k \tag{28}$$

Now, let us assume that the u_k are statistically independent random variables. This assumption is not true. We use this property for the sake of simplicity. In this case, we can derive the mean and variance of decision variable y as:

$$\begin{aligned} m &= \sum_{k=0}^{N-1} 4\mathrm{Re}\left[\overline{r_k}^* \overline{r_{\tau+k}}\right] \\ &= 4N h_0 h_1, \end{aligned} \tag{29}$$

and

$$\begin{aligned} v^2 &= \sum_{k=0}^{N-1} \left(24\sigma^2 \left|\overline{r_k}\right|^2 + 16\sigma^4\right) \\ &= N\left\{12\sigma^2\left(h_0^2 + h_1^2\right) + 8\sigma^4\right\}, \end{aligned} \tag{30}$$

respectively. Since the decision variable is the sum of a several statistically independent random variables, the distribution approaches a normal distribution followed by the central limit theorem. Error probability is given by

$$P = Q\left(\frac{m}{v}\right) \tag{31}$$

where

$$Q(x) = \frac{1}{\sqrt{\pi}} \int_{\frac{x}{\sqrt{2}}}^{\infty} e^{-t^2} dt \tag{32}$$

is a Q function. If we use 2 antennas, the error probability is given by

$$P = Q\left(\frac{m + m'}{\sqrt{v^2 + v'^2}}\right), \tag{33}$$

where m' and v'^2 are mean and variance of the other antenna, respectively. Substituting (29), (30) into (33), we can get the error rate as:

$$P = Q\left(\frac{2\sqrt{N}\left(h_0 h_1 + h_0' h_1'\right)}{\sigma\sqrt{3\left(h_0^2 + h_1^2 + h_0'^2 + h_1'^2\right) + 4\sigma^2}}\right). \tag{34}$$

Table 1: *Simulation parameters*

Channel model	AWGN
Spread spectrum	DS/SS
Modulation method	BPSK
Spreading code	Extended M-sequence
Chip length N	16
Carrier frequency	144 kHz
Transmission rate	1.2 kbps
Distance between transmitter antennas d	0.025 m
Antenna's radiuses l	0.01 m

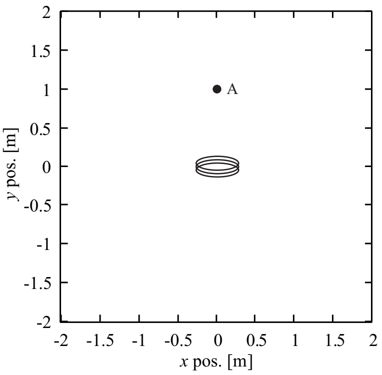

Fig.6: *Layout of an antenna array.*

Eq. (34) is the error rate function of received powers h_0, h_1, h'_0, h'_1. Received powers can easily be calculated from several parameters such as antenna gain, distance between antennas and propagation path loss factor.

6. DETERMINATION ERROR PERFORMANCE

In this section, we analyze the region determination error rate performance of the proposed region determination system. At first, we compare the theoretical value to the simulation result for confirming the validity of the analysis. Theoretical value is calculated from (34) by GSL (GNU Scientific Library) [15]. Simulator translates magnetic flux density (4), (5), (6) and (7) to signal power at the receiving point. Signals are received by one antenna with added AWGN, passes ADC, multiplied carrier and delayed itself, added another signals from the other antenna, passes LPF, and determined inside or outside. Simulator is made by IT++ library on C++ [16]. Table 1 shows the simulation parameters for analysis. We define receiver antenna gains are constant level. Electromotive force model is derived by (8) and (9). We define $k_1 = k_2 = 1$. Fig. 6 shows a layout of an antenna array. We set a transmit antenna L_2 at the origin $(x, y) = (0, 0)$ and two transmit antennas on the $(x, y) = (0, \pm 0.025)$. We set receiver on the $(x, y) = (0, 1)$. The angle between x-axis and the receive antenna θ is $\frac{\pi}{6}$ radian. Region determina-

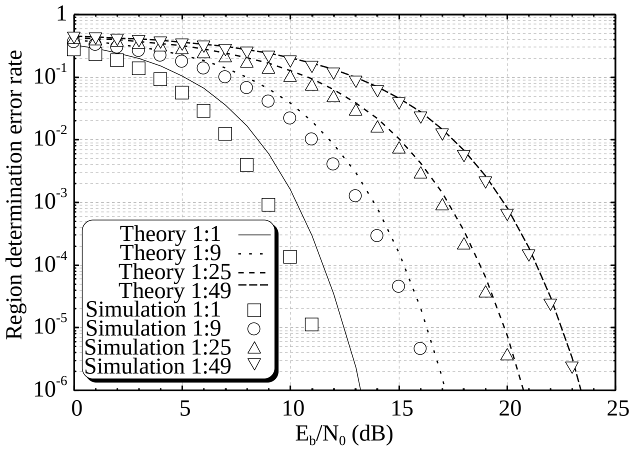

Fig.7: *Region determination error rate performance of the proposed positioning system.*

tion error rate is a rate that the receiver determinates different region from a region it is existing in. The error case is that the deterministic variance is negative here. Noise powers are same level of both receive antennas. Received power ratio of the delayed signals to the directed signals $h_1^2 + h_1'^2 : h_0^2 + h_0'^2$ have 4 levels $1:1, 1:9, 1:25, 1:49$. The rate of a sum of all received signals powers to a sum of all noise powers $(h_1^2 + h_1'^2 + h_0^2 + h_0'^2 : 2\sigma^2)$ denoted by E_b/N_0, are set from 0 to 25 dB. Fig. 7 shows region determination error rate between theoretical analysis and simulator. The theoretical analysis agrees well with the simulation result. When the power ratio is 1 : 1, we can observe difference between theoretical and simulation result. The difference is at most 1.3 dB at an error rate of 10^{-5}.

Second, we will show that contour graph for determining its existence region by decision variable (correlation value). Since we need to determine the region around the border in the keyless entry system, we show only the region around the transmitter. All currents are same. $I_1 = I_2 = I_3$ in (4), (5), (6) and (7). Signal to noise ratio of central antenna by 1 bit $h_0^2 + h_0'^2 : \sigma^2$ is 30 dB at A $(x, y) = (0, 1)$. Fig. 8 shows rate that correlation value z_d is negative. We can see in the figure that the inner product is positive with high probability in the upper half circular region in Fig. 8. While on the other hand, we can see in the figure that the inner product is negative with high probability in the lower half circular region in Fig. 8. The magnetic fields of both transmit antenna L_1 and L_3, and transmit antenna L_2 are same direction in the region y-axis is positive. And opposite direction in the region y-axis is negative. We find region determination is difficult in the region far from the origin, rates of negative correlation value and positive correlation value are almost same. This is because the receiver can't get adequate received signals power in the region far from the transmit antennas. Positive rate and negative rate of correlation value are almost

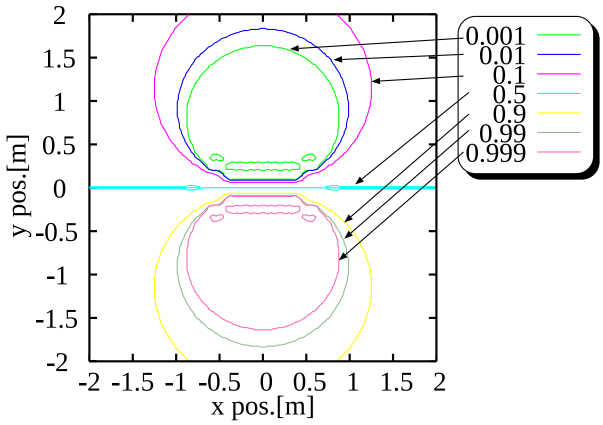

Fig.8: *Probability that the correlation z_d is negative.*

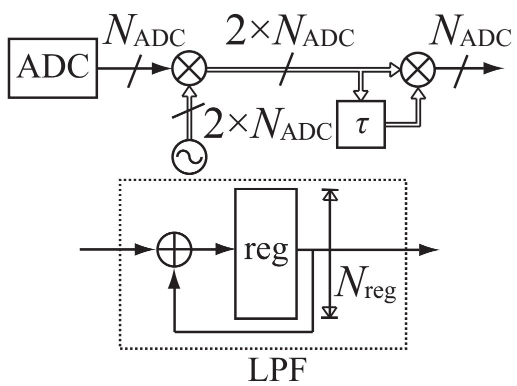

Fig.9: *Block diagram of receiver*

same in the region near y-axis and 1 m or more apart from x-axis. A magnetic field of L_1 and L_3, and of L_2 are close to orthogonal, because correlation value is close to 0.

7. REQUIRED RESOLUTION FOR ADC

The hardware complexity and power consumption depend on the bit resolution of the ADCs and the following signal processing component. In order to evaluate the hardware complexity, we first evaluate the bit error rate and the bit resolution of the ADCs in Fig. 9. Table 2 shows the frequency parameters for required resolution. We assume the sampling frequency of ADCs is 576 kHz. The received signals power is converted from 64-bit to some bits of ADC. Fig. 10 shows the relationship between the bit-resolution of ADCs and the determination error rate performance. In this analysis, we assume that there is no truncation and rounding errors throughout the signal processing followed by the ADCs. According to Fig. 10, the bit error rate performance degradation due to ADC is small when the resolution is 2-bit. Even if a 1-bit ADC (or comparasion) is used, the degradation is only around 1 dB. Therefore, if the hardware limitation is restricted, 1-bit ADC can be employed by 1 dB degradation. Fig. 11 shows

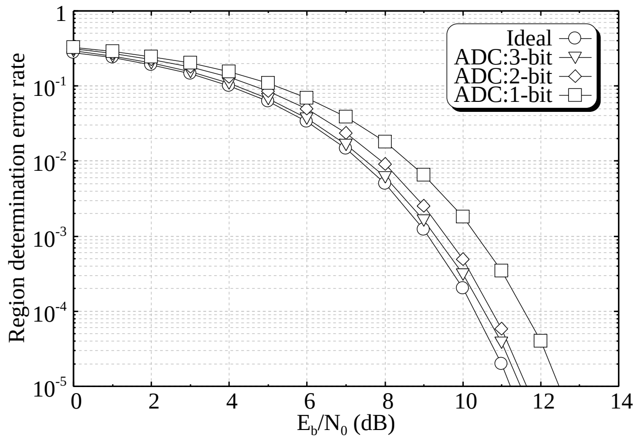

Fig.10: *Relationship between the ADC bit resolution and region determination error rate performance.*

Table 2: *Frequency parameters*

Chip length N	16
Carrier frequency	144 kHz
Transmission rate	1.2 kbps
Sampling frequency l	576 kHz

region determination error rate versus E_b/N_0 when max integrate and dump filter are restricted with a 3-bit ADC, and when ADC and integrate and dump filter is using 64-bit. The more max integrate and dump filter bit number, the error rate performance is better. 4-bit integrate and dump filter drop about 1.3 dB for ideal at error rate of 10^{-5}. 5-bit and 64-bit integrate and dump filter drop filter 0.25 dB for ideal line. Thus, proposed technique in this transaction can be thought that it is made up by 2-bit ADC and 5-bit integrate and dump filter.

8. CONCLUSION

In this paper, we have investigated the hardware complexity for the simple positioning scheme proposed by the antennas. The difference between theoretical analysis and computer simulation is at most 1.3 dB at error rate of 10^{-5}. We confirm that theoretical analysis can be used for evaluation of the region identification method. Computer simulation result shows that the proposed technique can identify the region of 2 to 3 meters at the region determination error rate of 10^{-2}. The required bit width for the propose scheme is made up by 2-bit ADC and 5-bit integrate and filter.

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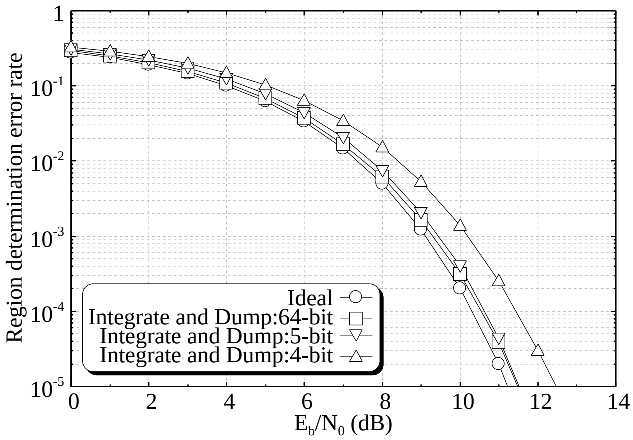

Fig.11: *Region determination error rate performance.*

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