Bit Error Rate Performance of ESPAR antenna-based Single-RF Diversity for IEEE802.15.4

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***Abstract*—This paper presents a single-RF diversity scheme for spread spectrum receiver based on IEEE 802.15.4 standard. The proposed scheme employs an Electronically Steerable Passive Array Radiator (ESPAR) antenna with periodically changing directivity at the symbol rate. IEEE 802.15.4 focuses on a low power consumption short range communication systems. However, the bit error rate performance is not good enough in a severe multipath fading environment. Diversity is a well-known technique to compensate the performance degradation due to multipath fading. However, the complexity for diversity reception is a major problem. In this paper, we propose a new single-RF diversity scheme using ESPAR antenna with periodically changing directivity. The proposed scheme is capable of obtaining the diversity gain in a frequency selective fading environment and it solves the slow convergence rate problem in the conventional ESPAR antenna based diversity scheme. Computer simulation result and theoretical analysis show that the proposed scheme gives diversity gain.**

***Index Terms*—IEEE802.15.4, Zig-Bee, diversity, ESPAR**

I. INTROCUTION

Diversity is a efficient technique capable of mitigating the performance degradation due to fading and is used in wide range of wireless communication systems such as mobile communication, Wireless LAN (Local Area Network), and PAN (Personal Area Network) systems.

In case of space diversity, signals are received by two or more antennas, and the received signals are combined in order to reduce the attenuation. The received signal occasionally attenuated and its strength falls below the thermal noise level due to fading. Since the amount of attenuation due to fading is different from each other when the antennas are spatially separated, the probability of deep fade after combining can be reduced and drastically improves the transmission performance.

There are a lot of combining technique for diversity reception such as selection combining, equal gain combining, and maximum ratio combining. Among them, the maximum ratio combining diversity is known to be the optimum in terms of maximizing the signal to noise power ratio (SNR) after combining.

However, the maximum ratio combining has a major drawback in terms of required hardware complexity. The maximum ratio combining receiver requires RF (Radio Frequency) front-end, ADC (Analog to Digital Converter), and baseband demodulation circuitry for each antenna branches, that is, it rises the power consumption of the receiver. In case of handheld terminals where the power consumption is strictly limited, it is difficult to apply the maximum ratio combining diversity.

In order to solve this problem, switch diversity scheme was used. It first chooses either one of the elements, and change the element when the received signal strength falls below the predetermined threshold. Although the switch diversity scheme is efficient in terms of reducing the hardware complexity, the diversity gain is small compared to the maximum ratio combining. Furthermore, it is not capable of tracking the fast variation of the channel because of the nature of feedback control.

Recently, the passive array antenna called ESPAR (Electronically Steerable Passive Array Radiator) antenna has been proposed [1]. ESPAR antenna is composed of a director and the parastic elements which are placed in the vicinity of the director. The parastic elements are terminated by the varactor diode. The beam pattern can be controlled by changing the reactance values of the varactor diode.

A diversity receiver using ESPAR antenna has been proposed. The principle operation of the diversity is the same as that of the switch diversity. That is, it inherits the diversity gain and tracking problems in the switch diversity.

In order to solve this problem, we propose a diversity using fast directivity controlled ESPAR antenna. A part of authors has already proposed a fast directivity contolled ESPAR antenna based diversity receiver for OFDM (Orthogonal Frequency Division Multiplex) [2]. This scheme makes efficient use of ICI (Inter-Channel Interference) caused by the fast motion of directivity. This ICI can be eliminated because the motion of directivity is known at the receiver. By using the MMSE (Minimum Mean Square Error) frequency domain equalizer after FFT (Fast Fourier Transform), we can get an implicit diversity gain. Since this scheme does not require feedback control and switching, we can solve the problems in switch diversity. Furthremore, the proposed scheme is efficient in a severe frequency selective fading channel.

This paper proposes a diversity receiver based on fast directivity controlled ESPAR antenna for IEEE 802.15.4 which employs direct sequence spread spectrum. In IEEE 802.15.4, 250kbit/s of binary data are divided into 4-bit blocks and mapped onto the 16-level symbol. Then the transmitter

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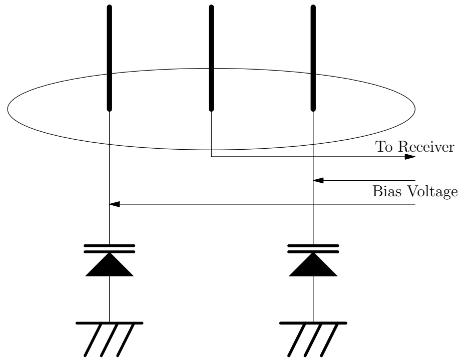

Fig. 1. A typical ESPAR antenna structure

chooses one of the 16 spreading sequences depending on the symbol. The proposed scheme changes the steering pattern of the ESPAR antenna at 62.5kHz which is the same as the symbol rate of the IEEE 802.15.4 standard. Despite OFDM systems, IEEE 802.15.4 is robust to the distortion due to fast variation of the channel, the proposed scheme gives the diversity gain without equalizations. Other elements in the vicinity of the director are terminated by the variable capasitors. These elements are referred to as the parastic elements. Therefore, the steering beam pattern varies depending on the bias voltages applied to the variable capasitors.

The rest of paper is organized as follows. Section 2 illustrates the principle of ESPAR antenna followed by the physical layer signaling of the IEEE 802.15.4 standard in Section 3. Section 4 proposes an ESPAR-antenna based diversity scheme for IEEE 802.15.4. Section 5 shows the bit error rate performance of the proposed scheme by computer simulation.

II. Principle of ESPAR Antenna

Fig. 1 shows a typical configuration of ESPAR antenna. ESPAR antenna is composed of three quarter-wavelength monopole antennas. Although ESPAR antenna has one RF port, it is capable of steering the beam pattern similar to the well-known adaptive array antennas having multiple RF ports. The ESPAR antenna in Fig. 1 is composed of three monopole antennas, each of which is quarter-wavelength antenna. The director at the middle of the array is connected to the RF input of the receiver. Two other elements in the vicinity of the director are terminated by the variable capasitors. These elements are referred to as the parastic elements. The phase of the induced currents flows at the parastic elements can be controlled by the reactance value according to the bias voltages. Therefore, the steering beam pattern varies depending on the bias voltages applied to the variable capasitors connected to the parastic elements.Since the variable capacitors, which terminate to parastic elements,are passive devices, and their reactance value are controlled by the bias voltages.ESPAR antenna does not consume the power in principle.

As applications of ESPAR antennas, estimation of the arrival direction of the signal using MUSIC (multiple signal classification) method or ESPRIT (estimation of signal paramters via rotational invariance technique) method have been proposed [3,4]. Hasuike et al. [5] proposed on use of ESPAR antenna for wireless ad-hoc network in order to reduce radio interference. However, this method require modifications in MAC layer protocol.

The diversity receiver based on ESPAR antenna has also been proposed as mentioned in introduction. However, the conventional ESPAR antenna-based diversity receiver is not efficient in terms of diversity gain and tracking capability.

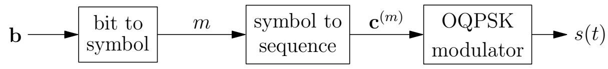

Fig. 2. Block diagram of the transmitter based on IEEE 802.15.4 PHY standard

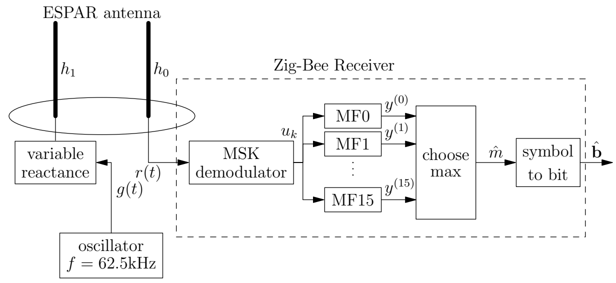

Fig. 3. Block diagram of the proposed receiver

III. IEEE 802.15.4 PHY standard

Fig. 2 illustrates the block diagram of the transmitter based on IEEE 802.15.4 physical layer standard. Four-bit block $\mathbf{b} = (b_0, b_1, b_2, b_3)$ is mapped onto the 16-level symbol according to the conversion formula, $m = 2^3 b_3 + 2^2 b_2 + 2b_1 + b_0$ at the bits-to-symbol converter. One of 16 spreading sequences is chosen according to the symbol at the symbol-to-sequence converter. The output sequence is given by $\mathbf{c}^{(m)} = (c_0^{(m)}, c_1^{(m)}, \ldots, c_{31}^{(m)})$. This spreading sequence is applied to OQPSK (Offset Quadrature Phase Shift Keying) modulator to generate the transmit signal. The output of the OQPSK modulator in the equivalent low pass expression is given by

$$s(t) = \sum_k c_{2k} f(t-2kT_b) + j \sum_k c_{2k+1} f(t-(2k+1)T_b), \quad (1)$$

where a sinusoidal waveform is chosen as a spreading chip pulse waveform. The pulse waveform is given by

$$f(t) = \begin{cases} \cos\left(\dfrac{\pi t}{2T_b}\right); & (|t| \leq T_b) \\ 0; & (|t| > T_b) \end{cases} \quad (2)$$

where $T_b = 1/(2 \times 10^6) = 5 \times 10^{-7}$ is the chip duration.

IV. Proposed ESPAR Antenna-based Diversity Receiver

Fig. 3 shows the block diagram of the proposed ESPAR-antenna-based diversity receiver for IEEE 802.15.4. The steering beam pattern varies at a frequency of $T_s = 1/(32T_b) = 62.5$kHz, which is the same as the symbol rate.

In the following, we assume a slow Rayleigh fading channel. The received signal at the output of the ESPAR antenna is then given by

$$r(t) = (h_0 + h_1 g(t))\, s(t) + z(t), \tag{3}$$

where h_i $(i = 0, 1)$ represents the attenuation and phase rotation due to fading. In Rayleigh fading channel, h_i is a zero-mean complex Gaussian random variable. $g(t)$ is the channel variation due to the change in the steering beam pattern of the ESPAR antenna. Furthermore, $z(t)$ is an additive white Gaussian noise (AWGN) component. By substituting Eq. (1), we can rewrite the received signal as

$$r_k = (h_0 + h_1 g_k)\, d_k + z_k, \tag{4}$$

where

$$d_k = \begin{cases} c_k & (\text{even } k) \\ jc_k & (\text{odd } k) \end{cases}, \tag{5}$$

where $r_k = r(kT_b)$, $g_k = g(kT_b)$, and z_k AWGN component after sampling.

The received signal is then applied to the non-coherent MSK (Minimum Shift Keying) demodulator. The output of the MSK demodulator is given by

$$u_k = \Im\left[r_k r_{k-1}^*\right]. \tag{6}$$

The output, u_k is applied to the bank of 16 matched filters (MFs). The impulse response of the m-th MF is given by

$$q_{2k}^{(m)} = \begin{cases} -1 & (c_{2k-1}^{(m)} = c_{2k}^{(m)}) \\ +1 & (c_{2k-1}^{(m)} \neq c_{2k}^{(m)}) \end{cases} \tag{7}$$

$$q_{2k+1}^{(m)} = \begin{cases} +1 & (c_{2k}^{(m)} = c_{2k+1}^{(m)}) \\ -1 & (c_{2k}^{(m)} \neq c_{2k+1}^{(m)}) \end{cases}. \tag{8}$$

The output of the m-th MF is then given by

$$y^{(m)} = \sum_{k=0}^{N-1} q_k^{(m)} u_k. \tag{9}$$

The output of the m-th MF, $y^{(m)}$, is fed to the maximum value selector. The symbol which maximizes the MF output $m = \hat{m}$ is supposed to be transmitted at the maximum value selector. The estimated symbol is applied to the symbol-to-bit converter to convert the bit stream, $\hat{\mathbf{b}}$.

V. Error Rate Analysis

Now, let us define the received signal after sampling as $w_k = (h_0 + h_1 g_k) + z'_k$. The received signal is represented in vector-form as:

$$\mathbf{w} = [w_0, w_1, \ldots, w_{N-1}]^T, \tag{10}$$

Then, the m-th MF output can be expressed in quadratic form as:

$$y^{(m)} = \mathbf{w}^H \mathbf{F} \mathbf{w}, \tag{11}$$

where

$$\mathbf{F} = \begin{bmatrix} 0 & 1 & 0 & \cdots & & 0 \\ 1 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 1 & 0 & 1 & 0 & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & 1 & 0 & 1 \\ 0 & & \cdots & 0 & 1 & 0 \end{bmatrix}, \tag{12}$$

is a matrix representing the demodulator and MF.

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

$$\begin{aligned} \mathbf{R} &= \frac{1}{2} E\left[\mathbf{w}^* \mathbf{w}^T\right] \\ &= \left[\rho_{ik}\right]_{i,k=0,1,\ldots,N-1}, \end{aligned} \tag{13}$$

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

$$\rho_{ik} = \begin{cases} b + \sigma_z^2 & (i = k) \\ \frac{b}{2}\left(1 + g_i^* g_k\right) & (i \neq k) \end{cases}, \tag{14}$$

where b is the average received signal power, and σ_z^2 is the variance of the AWGN component.

Now we can derive the pairwise error probability that the m' is transmitted when m was transmitted. Suppose that the probability density function of $X = y^{(m)}$ is defined as $p(X)$. The pairwise error probability is given by

$$\begin{aligned} P\{m \rightarrow m'\} &= \int_{-\infty}^{0} p(X) dX \\ &= \int_{-\infty}^{0} \int_{-\infty}^{\infty} G(\xi) \exp(-j\xi X)\, d\xi dX \\ &= \int_{-\infty}^{\infty} \frac{G(\xi)}{\xi} d\xi \end{aligned} \tag{15}$$

where $G(\xi)$ is the characteristic function of $X = y^{(m)}$, and given by

$$G(\xi) = \frac{1}{\det\left(\mathbf{I} - 2j\xi \mathbf{R}^* \mathbf{F}\right)} \tag{16}$$

Let $C = \{\lambda | \det(\mathbf{A} - \lambda \mathbf{I}) = 0\}$ be a set of all the eigen-values of $\mathbf{A} = 2\mathbf{R}^*\mathbf{F}$. The characteristic function is further rewritten as

$$G(\xi) = \left[\prod_{\lambda \in C} (1 - j\lambda\xi)\right]^{-1} \tag{17}$$

From the above analysis, the pairwise error probability is given by

$$P\{m \rightarrow m'\} = \sum_{\lambda \in C_m} \left[\prod_{\substack{\lambda' \in C \\ \lambda' \neq \lambda}} \left(1 - \frac{\lambda'}{\lambda}\right)\right]^{-1} \tag{18}$$

where $C_m = \{\lambda | \lambda \in C, \Re[\lambda] < 0\}$ of $\mathbf{A}$ is a set of eigenvalues whose real components are negative.

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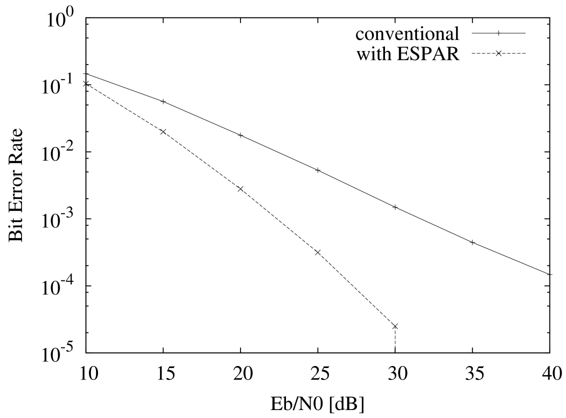

Fig. 4. Bit Error Rate Performance of the Proposed Diversity Receiver

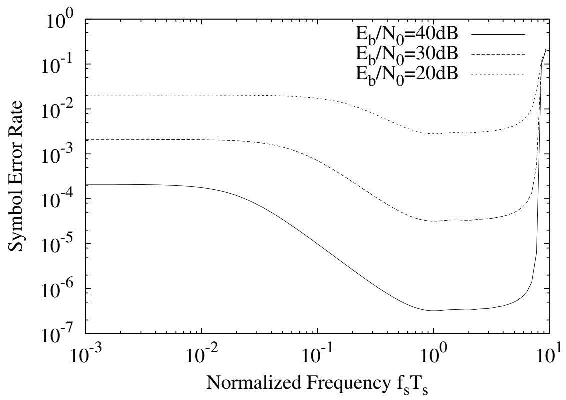

Fig. 5. Error Rate Performance against the normalized frequency for directivity change

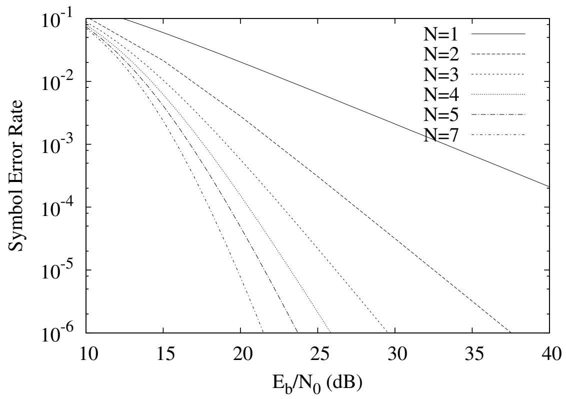

Fig. 6. Error Rate Performance against the number of elements

VI. Numerical Ayalysis

In this section, we analyze the bit error rate performance of the proposed diversity receiver by computer simulation. In the following, we assume that the function corresponding to the fast time variation of steering beam pattern is given by

$$g_k = \exp\left(\frac{j2\pi\alpha t}{T_s}\right) \tag{19}$$

where α is the beam pattern variation frequency normalized by the symbol rate ($1/T_s = 62.5$kbit/s).

Fig. 4 shows the bit error rate performance of the proposed scheme. In this figure, we assume $\alpha = 1$. We can confirm that proposed scheme gives diversity gain.

Now, the bit error rate against the steering beam pattern variation frequency is shown by making use of Eq. (18). Fig. 5 shows the symbol error rate performance against the normalized variation frequency. We can not get the diversity gain when the normalized frequency of beam pattern variation is less than 0.5. This is because the received signal strength variation is reduced. On the other hand, the symbol error rate drastically degrades when the normalized frequency exceeds 5 since the distortion due to beam pattern variation affects the detection. From this result, we have to set the normalized frequency for $0.5 < \alpha < 5$. It also shows that it is no need to synchronize the frequency to symbol rate.

In the discussions above, we assume the two-element ESPAR antenna. However, further improvement in error rate performance could be possible if we use two or more parastic elements. Now, let us assume that the control frequency for l-th parastic element is $k\alpha$. Fig. 6 shows the impact of the number of ESPAR antenna elements to the symbol error rate performance. From this figure, we can further improve the error rate performance.

VII. Conclusion

This paper proposed the single-RF diversity receiver using fast steering beam pattern controlled ESPAR antenna for IEEE 802.15.4. The proposed scheme is capable of obtaining diversity gain by changing the steering beam pattern at the frequency of symbol rate. Computer simulation result showed that the proposed scheme efficiently get the diversity gain in a Rayleigh fading environment. Further improvement is possible by increase in the number of parastic elements.

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