Novel Receive Diversity Scheme Using ESPAR Antenna and Arbitrary Frequency Band

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***Abstract*—This paper proposes a novel receive diversity scheme which uses Electronically Steerable Passive Array Radiator (ESPAR) antenna in which reactance connected to parasitic antenna element is oscillated by sinusoidal waveforms of arbitrary frequencies. By controlling the frequency applying to the reactance, we can use frequency bands both assigned and not assigned to the corresponding communication systems without causing any interference to the signals used in the band. We propose several receiver structures for Orthogonal Frequency Division Multiplexing (OFDM) systems and evaluate Bit Error Rate (BER) to confirm the effect of the proposed diversity scheme with Maximum Ratio Combining (MRC) and Selection Combining (SC).**

I. Introduction

In wide-band wireless communications, multipath fading is a significant problem since it causes frequency selective fading. Orthogonal Frequency Division Multiplexing (OFDM) schemes are well-known as a suitable modulation scheme possessing robustness against the multipath or the frequency selective fading [1], [2] and have been developed to improve the performance. Because of the robustness and its high spectral efficiency, OFDM schemes have been employed in standards such as terrestrial digital broadcasting, wireless Local Area Network (LAN), wireless Metropolitan Area Network (MAN), and so on [3]–[7]. However, even if OFDM schemes are used, it is difficult to recover severely degraded subcarrier components due to the frequency selective fading. One of promising methods to improve the performance of degraded subcarriers is receive diversity with multiple antennas.

In general such diversity scheme requires distances between antennas more than half-wavelengths and multiple receivers. Therefore, as the the number of diversity branches increases, the number of Radio Frequency (RF) front-ends and the receiver size can be larger.

To solve the size problem, a single-RF diversity reception using Electronically Steerable Passive Array Radiator (ESPAR) antenna whose beam direction is changed at frequency of the OFDM symbol rate has been proposed for OFDM systems [8]. In ESPAR antenna, parasitic antennas are settled close to the main antenna to exploit the effect of electrical coupling and terminated by an element of variable reactance [9], [10]. Since the distance between the antennas can be 10 % of wavelength, the total antenna size can also be smaller than that of the conventional receive diversity with multiple antennas. Moreover, since current does not flow at the parasitic antenna, ideally there is no additional power consumption due to attaching the parasitic antenna. In the diversity scheme of [8], the reactance of the parasitic antenna is changed by applying sinusoidal voltage of the frequency of symbol rate of OFDM signals. The oscillation of the reactance induces frequency-shift by the symbol rate to the received signal at the parasitic antenna. Then the frequency-shifted signal can be also obtained at the main antenna through electrical coupling. Since the frequency-shift can correspond to generating time-varying beam direction of ESPAR antenna, the signal from the parasitic antenna could suffer independent fading of the received signal. Thus, it is expected to obtain the same diversity gain as the conventional scheme by the scheme [8].

One of problems of the diversity scheme might be the computational complexity. The signal processing needs accurate channel estimation of both signals received at the main and the parasitic antennas even the received signals including pilot symbols also overlap each other. Besides, the scheme requires calculation of the inverse matrices for channel estimation and equalization and is difficult to apply well-known Maximum Ratio Combining (MRC) and/or Selection Combining (SC).

To solve the problem, we propose a generalized scheme of the conventional diversity scheme proposed in [8]. In the proposed scheme, we consider arbitrary frequency for the oscillation of the reactance to prevent spectral overlapping [1]. By generalizing the frequency we can shift the spectrum of the received signal at the parasitic antenna toward arbitrary frequency region. If the frequency region is unused, or in some cases even used, we can receive and obtain two signals which suffer independent fading, from the main antenna in normal frequency band e.g. 2.4 GHz for WLAN systems using 2.4 GHz band, and another is from the parasitic antenna in arbitrary frequency band, e.g. adjacent channels, that allocated for cellular systems, or TV white-space, and so on. We also propose several receiver structures to achieve the proposed diversity scheme and show primary numerical results by computer simulation. The BER performances indicate that we can obtain the benefit of MRC and SC similar to the conventional receive diversity schemes which use two independent antennas

[1]Part of the ideas presented in domestic conferences [11], [12]

placed separately and two OFDM receivers.

In Section II, we show a system model of OFDM systems with ESPAR antenna. Then proposed diversity schemes is explained in Section III and receiver structures are discussed in Section IV. Some numerical results are given in Section V. Concluding remarks are described in Section VI

II. System Model

We consider OFDM systems with ESPAR antenna at the receiver. The system model is shown in Fig. 1.

At the transmitter, binary data sequences are sent to a modulator to generate modulated symbols $\boldsymbol{x} = [x_0, x_1, \ldots, x_{N_d-1}]^T$ according to modulation schemes such as Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM), where N_d is the number of data symbols per OFDM symbol. The output symbol sequence is changed to parallel sequences by Serial-to-Parallel (S/P) converter.

Similarly, pilot symbols $\boldsymbol{p} = [p_0, p_1, \ldots, p_{N_d-1}]^T$ for channel estimation are modulated and input to S/P converter. We add pilot symbols $\boldsymbol{p}$ before the OFDM symbols including data symbols $\boldsymbol{x}$ and input both pilot and data symbols into Inverse Fast Fourier Transform (IFFT) with FFT point of N_f. We do not use dc component and place $N_d/2$ data symbols symmetrically about dc in both positive and negative frequencies. The frequency space between neighboring subcarriers is assumed to be f.

Then Cyclic Prefix (CP) is inserted into Guard Interval (GI) of length N_{GI} placed before the IFFT output. The GI and the IFFT output constructs an OFDM symbol. The signal is then Parallel-to-Serial (P/S) converted and carried to Digital-to-Analogue (D/A) converter. After the conversion, the signal is frequency modulated by a carrier frequency f_c and transferred to transmit antenna and the air.

As a communication channel, we consider multipath fading consisting of Rayleigh faded paths and Additive White Gaussian Noise (AWGN) channel.

We call the antenna which directly connected to OFDM receiver a main antenna. We place a parasitic antenna near the main antenna, i.e., the distance between the antennas tends to within a half-wavelength. The combined antenna is called as ESPAR antenna [9], [10]. The parasitic antenna does not connect to the OFDM receiver, however, by electrical coupling the antenna can induce the received signal to the main antenna and thereby the OFDM receiver. In this study, for simplicity we assume to apply voltage waveform expressed as $e^{j2\pi f_s t}$ to the variable reactance of the parasitic antenna. Here f_s means the frequency-shift caused by the sinusoidal waveform excited at the reactance. In this study, we set $f_s = N_s f$, where N_s means the amount of frequency-shift by unit of subcarrier interval. Therefore the number N_s indicates the amount of frequency shift applied to the received signal at the parasitic antenna.

From the main antenna, we can receive a general OFDM signal with the central frequency of f_c. On the other hand, from the parasitic antenna, received signals which suffered statistically independent fading in the frequency band shifted by f_s from the carrier frequency f_c, i.e. $f_c + f_s$.

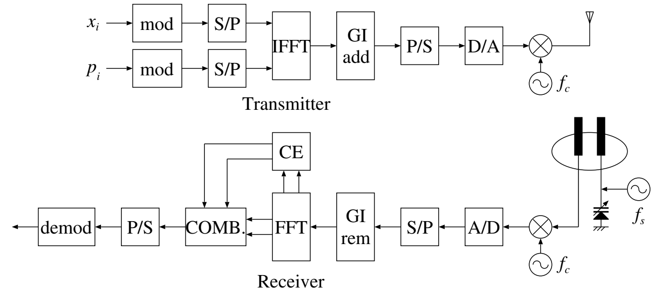

Fig. 1. System model of OFDM systems with ESPAR antenna whose parasitic antenna element is oscillated by frequency of f_s.

In the receiver, the received signal composed of two signals with the center frequency is f_c and $f_c + f_s$ is downconverted by a local oscillator with carrier frequency of f_c. In Section III, we give detailed descriptions of the receivers for the proposed schemes. Thus, the common part of the receiver is described in this section. The baseband signals are transferred to Analogue-to-Digital (A/D) converter. Then, after passing S/P converter, GI part of OFDM symbols is removed to construct input signals to FFT. The application of FFT can generate parallel subcarriers to be detected.

To estimate channel conditions, firstly pilot symbols are extracted and sent to Channel Estimator (CE) to estimate channel coefficients. By the estimates we can compensate (equalize) the effect of channel. Then, the equalized FFT outputs should be combined by MRC or SC to achieve maximum diversity gain. Combined decision variables are applied to S/P converter and demodulator to obtain the demodulated symbols.

III. Receive Diversity Scheme with ESPAR Antenna

In this section, we describe the proposed receive diversity scheme, which uses ESPAR antenna oscillated by sinusoidal waveform, by comparing to the conventional scheme.

A. Conventional receive diversity scheme using ESPAR antenna

A single-RF receiver diversity reception scheme using ESPAR antenna has been proposed to reduce the number of RF front ends and its antenna size [8]. In the scheme, voltage forming sinusoidal waveform of frequency $f_s = f$ changes the reactance connected to the parasitic antenna in ESPAR antenna. Here, the frequency f is the same as the OFDM symbol rate or subcarrier interval in the frequency domain. Therefore, due to applying the voltage ESPAR antenna receives both signals with the central frequency of f_c and that of $f_c + f$.

The spectral shape of the received signals by the conventional scheme is shown in Fig. 2. From the figure, we can see that neighboring subcarrier components overlap and interfere each other. Thus the conventional scheme employs Minimum Mean Square Error (MMSE) equalization for decomposing the overlapped spectra, equalizing both signals, and combining them [8].

B. Concept of the proposed receive diversity scheme

We propose receive diversity scheme using ESPAR antenna with oscillation of the reactance by arbitrary frequency $f_s = N_s f$. We set the amount of frequency shift $N_s > 1$ (the case of $N_s = 1$ corresponds to the conventional scheme).

As for selecting N_s, we have the following conjectures about N_s to be satisfied.

1) $N_s > N_d$.
2) N_s is divisible by N_f / N_{GI}.

The first condition needs to keep the received signal components which suffer independent fading from both the main and the parasitic antennas orthogonal each other. Therefore, we can receive the benefits of conventional diversity combining schemes, e.g. MRC and SC, to obtain the diversity gain without setting another active antenna element separating more than half-wavelength. The spectra of the received signals when we apply the proposed scheme with satisfying the condition of N_s are shown as an example in Fig. 3. It can seen from the figure that we can receive the signals from both antennas without interfering each other due to the appropriate selection of N_s. Thus, complex signal decomposition techniques are no longer unnecessary like the conventional scheme.

The second condition requires to maintain the phase of applied waveform to the reactance constant at the beginning of every FFT window. The cases that the phase is kept ($N_s = N_f / N_{\mathrm{GI}}$) and the phase changes every OFDM symbol ($N_s < N_f / N_{\mathrm{GI}}$) are illustrated in Fig. 4. When $N_s \neq N_f / N_{\mathrm{GI}}$, since the phase at the beginning of FFT window varies, channel coefficients can also vary by the phase. Although the orthogonality between subcarriers can be kept, it requires to compensate the phase rotation in addition to channel compensation.

To achieve the schemes mentioned above, it is crucial to employ cognitive radio technology such as spectrum sensing for preventing interference with signals in the frequency regions where the signal received at the parasitic antenna are shifted. Such interference can happen when we use the neighboring channels, i.e. f_s is relatively small, as the frequency band where one received signal frequency-shifted. In this study, we assume that we can correctly detect that no user transmits any signal in the neighboring channel of the desired user's in such case.

However, if we can make f_s very large, the frequency characteristics of the antenna may reduce the level of the received signals in the frequency band far from f_c. In this case, spectrum sensing may be no longer required if the interference level can be sufficiently decreased. Instead of no requirement of channel sensing, we need to find a device which can operate at such fast speed of oscillation f_s. Since the device problem is beyond the area this paper covers, we assume ideal reactance.

In the next section, we discuss the receiver structures to achieve the proposed diversity schemes.

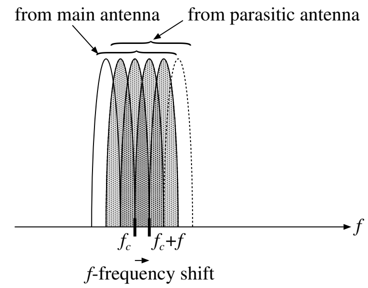

Fig. 2. Spectrum of the received signals by the conventional scheme where $f_s = f$ [8].

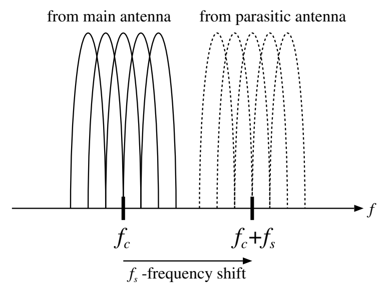

Fig. 3. Spectrum of the received signals by the proposed scheme with $f_s = N_s f$ frequency shift.

IV. Receiver structures to achieve the proposed receive diversity

In this section, we propose three receiver structures to achieve the proposed scheme described in Section III. Two of the three could be suitable for the scheme whose frequency shift is relatively smaller, i.e. using the neighboring channel or neighboring frequency band which might be assigned to the other system. Another structure can cover any frequency band as far as the reactance operate at high speed. However, it requires multiple receivers like conventional receive diversity schemes.

A. Proposed receiver structure: Type 1

As the first structure, we consider to increase the FFT size N_f until N_f can receive all the spectral components from both antennas. The receiver structure is shown in Fig. 1. We show the relation between the FFT size and the spectrum of the received signals by the proposed receiver in Fig. 5. In the figure, three FFT sizes are shown, i.e. N_f, $2N_f$, and $4N_f$,

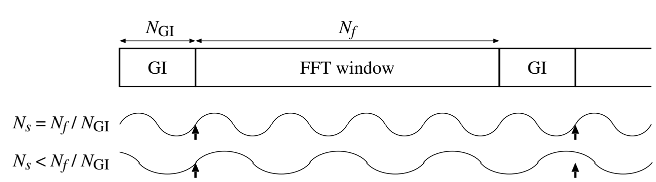

Fig. 4. Graphical relation between OFDM symbol and sinusoidal waveforms of frequency f_s applied to reactance.

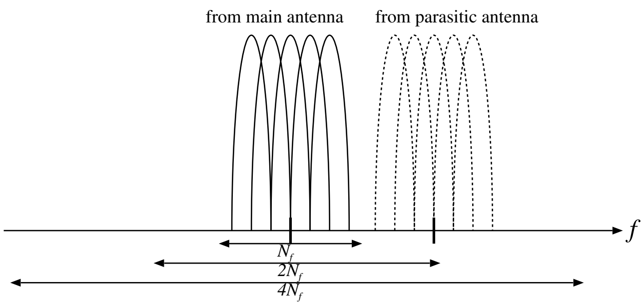

Fig. 5. Relation between FFT points and the spectra of the received signals by the proposed diversity receiver.

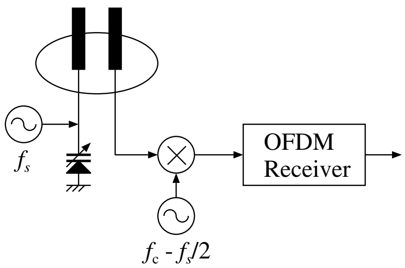

Fig. 6. The proposed receiver structure (Type 2).

and compared to the width of the spectrum of OFDM signals. Here we assume that $N_f < N_d$. As shown in the figure, even if we set $N_s = N_d + 1$, the minimum number of frequency-shift, FFT size of $2N_f$ cannot cover all the subcarriers without causing aliasing. Therefore, we need at least 4 times as large as the FFT size $4N_f$ required to accommodate N_d subcarriers to prevent the effect of aliasing and interference.

By setting the FFT size of $4N_f$ the receiver can divide the superimposed signals. However, such large FFT size can clearly be a problem in terms of computational complexity.

B. Proposed receiver structure: Type 2

Next, we propose a structure which frequency-shifts the combined signals from the main and the parasitic antennas by $f_s = -N_s f/2$ before the combined signals are input to OFDM receiver. The operation can be achieved by the receiver structure in Fig. 6. Since the frequency-shift above can be implemented by changing the frequency of the local oscillator from f_c to $f_c - f_s$, there is no need to add additional circuit for the frequency shift.

The situation of the received signal spectrum is shown in Fig. 7. From the figure, we can see that it is possible to reduce the FFT size from $4N_f$ to $2N_f$ for allowing both signals' spectrum without the aliasing. Double FFT size might not be so impractical, because Wi-Fi uses channel bonding techniques to bandle two neighboring channels.

C. Proposed receiver structure: Type 3

The third receiver structure is shown in Fig. 8. Type 3 might be the same receiver structure as conventional receivers except

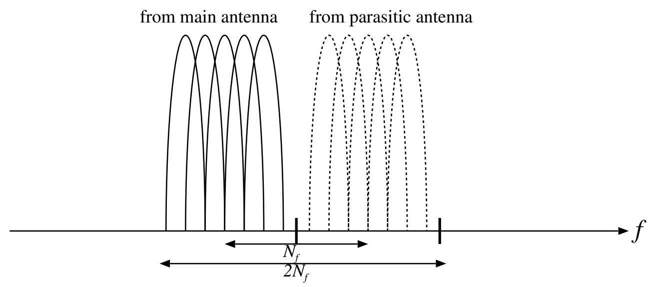

Fig. 7. Relation between FFT points and the spectrum of the received signals by the proposed receiver structure Type 2.

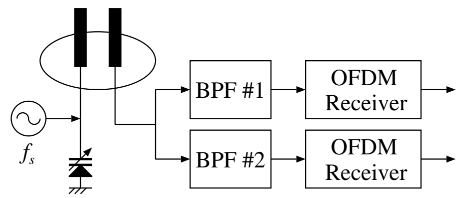

Fig. 8. The proposed receiver structure (Type 3).

for the use of ESPAR antenna to receive multiple signals suffering independent fading. This structure only can use large amount of the frequency-shift N_s, because the OFDM receivers are separated instead of employing single FFT like Types 1 and 2. By appropriate setting of Band Pass Filters (BPFs), we can prevent aliasing problem, keep the FFT sizes as N_f, and obtain diversity gain according to an appropriate combining method. When we select the frequency-shift N_s, it might be easier to use the frequency band so-called "white spaces" because channel sensing is unnecessary.

V. Numerical Examples

According to the system model and the receiver structures, we verify the BER performances of the proposed receive diversity schemes through computer simulations. Simulation parameters referred to IEEE 802.11a are shown in Table I [5]. Here we select $N_s = 56$ which is the minimum number to satisfy the conditions mentioned above. It is assumed that both signals received at the main and the parasitic antennas are suffered independent fading. We assume perfect channel estimation by using the pilot symbols. Note that the proposed schemes can apply not only to multi-carrier modulation schemes but any type of signaling schemes.

Although we evaluate the BER performances of the proposed schemes, the numerical examples show that all the schemes show almost the same performances in the given simulation conditions. This is theoretically true because every scheme can completely separate the combined signals and the fading and noise environments are equivalently the same each other. Thus we show the results obtained by using the receiver structure Type 1 due to the limitation of the pages.

First we show BER versus average Signal-to-Noise power Ratio (SNR) in 1-path fading channel in Fig. 9. We plot the

TABLE I
SIMULATION PARAMETERS.

Channel	Rayleigh fading + AWGN
Number of data subcarriers N_d	52
FFT point N_f	256 (Type 1), 128 (Type 2) 64 (Type 3)
Frequency shift in samples N_s	56
Modulation scheme of data	QPSK

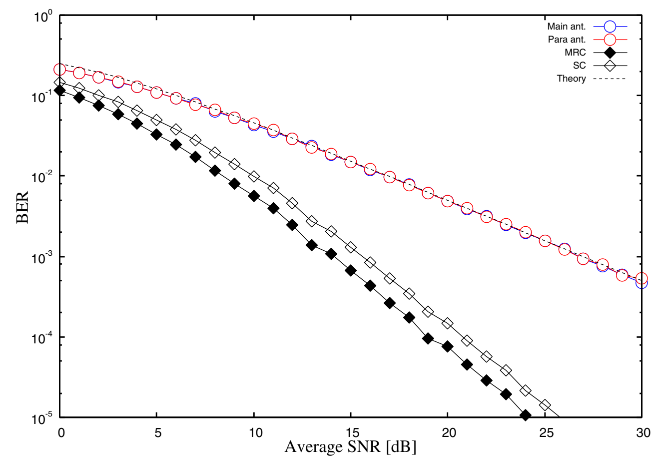

Fig. 9. BER versus average SNR of the proposed receiver Type 1 in 1-path Rayleigh fading channel.

curves obtained by the signal received by the main antenna only, that by the parasitic antenna only, the proposed diversity scheme with MRC and SC, and theoretical performances.

From the Fig. 9, we can see that the theoretical BER is almost the same as BER obtained by single (main or parasitic) antenna. Thus the received signals' behaviors in the simulator can have been verified. By using the MRC and SC, we can see that the improvements of the required SNR to achieve BER of 10^{-3} are 23 and 25 dB, respectively.

Then we evaluate the BER performances of the proposed scheme Type 1 under the environments of 2-path fading with equal path strength. The performances are shown in Fig. 10. The schemes used in the evaluations are the same as previous figure. From Fig. 10, it is also possible to reduce the BER by MRC and SC due to the diversity gain. However, the numbers of FFT point of Type 1 is relatively large even though the same performances can be obtained. Thus, in terms of practical viewpoint of FFT size, Type 3 and 2 might be feasible solutions.

VI. CONCLUSION

We proposed receive diversity schemes of OFDM by using ESPAR antenna whose reactance connected to the parasitic antenna is oscillated by an arbitrary frequency f_s. The schemes can separate combined received signals from the main and the parasitic antennas into two orthogonal OFDM signals by adequately selecting the frequency.

We also proposed three types of receiver structure which realizes the proposed diversity schemes. Although every structure can obtain the same BER performances under simple Rayleigh fading environments, they are different in terms of required FFT size, the number of OFDM receivers, available frequency band for the signal from the parasitic antenna, and necessity of channel sensing.

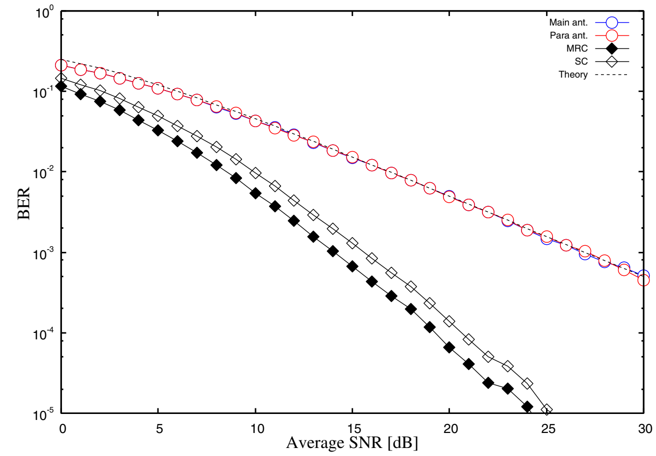

Fig. 10. BER versus average SNR of the proposed receiver Type 1 in 2-path Rayleigh fading channel.

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