Application of DFT Spreading to OFDM Based WLAN for Energy Efficiency Improvement

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Abstract— **This paper describes an application of Discrete Fourier Transform (DFT) spreading to Orthogonal Frequency Division Multiplexing (OFDM) based wireless LAN (WLAN) to reduce Peak to Average Power Ratio (PAPR) for energy efficiency improvement and to maintain robustness to DC offset error for cost-effective hardware implementation. We call our proposed scheme null DC sub-carrier DFT spreading OFDM, where the DC sub-carrier is made null by splitting the spectrum in the frequency domain after DFT spreading of the modulated signals. The computer simulation results confirm that BER performance is not degraded due to DC offset error at the transmitter and/or the receiver like OFDM with null DC sub-carrier and its PAPR is lower than OFDM, and is almost the same as the conventional DFT spreading OFDM.**

Keywords-DFT spreading; OFDM; Null; DC sub-carrier; PAPR

I. INTRODUCTION

Wireless local area networks (WLANs) have been widely accepted as a means of broadband wireless access to Internet and have been deployed in various environments such as home, campus and office. According to the increasing demand for mobile/nomadic access to the Internet services, hot spot services based on IEEE802.11a/g/n WLAN standards using 2.4GHz and 5GHz bands are becoming more and more popular in these days to off-load the cellular traffic to WLANs, since most of all mobile personal computers (PCs) and smart phone devices have WLAN access capability. In order to increase the bit rate and throughput of WLAN, IEEE802.11ac/ad are being standardized aiming at multi Gbps broadband access and IEEE802.11ah using UHF band such as 700MHz and 900MHz bands is also being standardized for cellular traffic offload applications and wireless sensor network applications [1]-[3].

As well known, orthogonal frequency division multiplexing (OFDM) is adopted in IEEE802.11a/g/n and will be used in IEEE802.11ac/ad as well due to its robustness to the severe frequency selective fading in mobile environments. OFDM shows excellent transmission performance under severe multi-path fading in mobile environments however the weak point of OFDM is its higher peak to average power ration (PAPR) than that of the conventional single carrier modulation scheme. This high PAPR can be a burden for battery-operated mobile terminal implementation because large output back-off (OBO) required in high power amplifier (HPA) could result in large power consumption. Therefore, IEEE802.11ad specification has an alternative PHY of single carrier modulation in addition to OFDM [1]. For the same reasons, discrete Fourier transform (DFT) spreading OFDM based single carrier-frequency division multiple access (SC-FDMA) has been adopted for the uplink transmission, i.e., from the mobile terminal to the base station, in 3GPP-LTE [4]. As DFT spreading OFDM (DFTs-OFDM herein after) is essentially a single carrier modulation based block transmission scheme, lower PAPR than OFDM can be achieved [5]. In addition, its power spectrum is as compact as that of OFDM. Furthermore, its robustness to the frequency selective fading is also equivalent to OFDM since cyclic prefix (CP) is introduced to avoid the inter-symbol interference due to frequency selective fading [6].

On the other hand, OFDM has another advantage of its robustness to DC offset error for cost-effective hardware implementation, i.e., precise DC offset adjustment is not required at modulator and demodulator since DC sub-carrier is made null in the OFDM based WLAN standards. For example, IEEE802.11a standard uses 52 sub-carriers based on 64 point FFT/IFFT, where DC sub-carrier is not used because BER performance of the DC sub-carrier can be significantly degraded due to DC offset error between D/A converter and I/Q modulator and/or that between I/Q demodulator and A/D converter. Therefore, null DC sub-carrier in OFDM is an important feature of OFDM for cost-effective hardware implementation in WLAN. As mentioned above, DFTs-OFDM is a promising solution to reduce PAPR, however we need to maintain the robustness to DC offset error when we apply DFT spreading to OFDM based WLAN.

In order to solve the above-mentioned problem for the application of DFT spreading to OFDM based WLAN, this paper proposes spectrum splitting after DFT spreading to make DC subcarrier null. In this paper, this new type of DFTs-OFDM is called a null DC sub-carrier DFTs-OFDM, which can achieve both advantages of low PAPR and robustness to DC offset error.

This paper is organized as follows: Section II describes the principle of the proposed null DC sub-carrier DFTs-OFDM (NDCS-DFTs-OFDM, hereinafter), Section III shows the performance evaluation results of NDCS-DFTs-

OFDM by computer simulation, for example PAPR, BER performance and Error Vector Magnitude (EVM) degradation due to DC offset error. They are compared with those of conventional DFTs-OFDM and OFDM. Finally, Section IV concludes this paper.

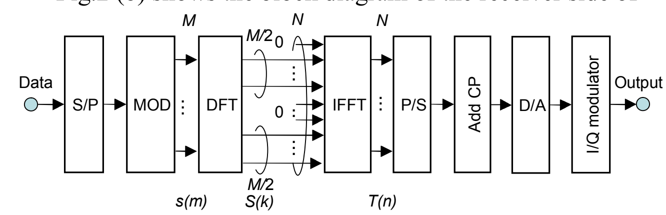
II. PRINCIPLE OF NDCS-DFTS-OFDM

A. Configulation of NDCS-DFTs-OFDM

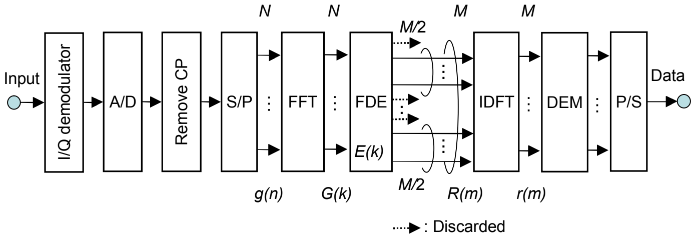
The block diagram of the proposed NDCS-DFTs-OFDM is shown in Fig. 1, where Fig.1 (a) shows the transmitter side and Fig.1 (b) shows the receiver side.

As shown in Fig.1 (a), the input data is converted from serial data to M symbols of parallel data, by which M sub-carriers are modulated. M points DFT spreading (pre-coding) is performed for M modulated sub-carriers. Then, M points of DFT spread modulated signals are fed to N points IFFT processor to generate OFDM signals, where N is set at power of two to employ FFT algorithm for reducing signal processing complexity. We assume M is an even number and $M<N$. In the input of IFFT, M point data are divided into two groups and $M/2$ point data are fed to the upper frequency part of IFFT processor input and the other $M/2$ point data are fed to the lower frequency part of IFFT processor input. DC component of the modulated signals is not transmitted by DC sub-carrier, but another sub-carrier. DC sub-carrier with frequency=0 is not used and null data is set at DC sub-carrier in the OFDM signals to avoid the BER performance degradation due to DC offset error. As the DFT spread modulated signals are divided to two parts, PAPR is expected to be slightly larger than that of the conventional DFTs-OFDM due to the insertion of null at DC sub-carrier, but it will be much smaller than that of OFDM. As DC sub-carrier is made null, the modulated signals are not affected by DC offset error between D/A converters and I/Q modulator.

Fig.2 (b) shows the block diagram of the receiver side of



(a) Transmitter side



(b) Receiver side

Figure 1. Block diagram of Null DC sub-carrier DFT spreading OFDM scheme (NDCS-DFTs-OFDM).

NDCS-DFTs-OFDM, where the output of the I/Q demodulator output is fed to A/D converters and CP is removed. As the received signal has no DC component, DC offset error between I/Q demodulator and A/D converters does not affect BER performance. This feature is essentially the same as the OFDM, which does not use DC sub-carrier. After A/D conversion, the received signals are fed to N point FFT and converted to frequency domain signals, where $M/2$ point data at the upper frequency part and the other $M/2$ point data at the lower frequency part are combined to the original modulated signals after DFT spreading at the transmitter, where DC sub-carrier is discarded. M point DFT spreading OFDM signals are fed to M point IDFT processor after frequency domain equalization (FDE). The output of the IDFT processor is demodulated on a sub-carrier by sub-carrier basis.

B. Mathematical expressions of NDCS-DFTs-OFDM

Mathematical expressions of the proposed NDCS-DFTs-OFDM based on the block diagram shown in Fig. 1 are given here.

Let us consider the transmitter side first. We assume that the size of DFT and IDFT is M where M is an even number. Supposing that the complex envelop of the modulated signal is $s(n)$ (n=0~M-1), discrete Fourier transform of $s(n)$, $S(k)$ (k=0~M-1) is given by

$$S(k)=\sum_{n=0}^{M-1} s(n) e^{-j\frac{2\pi}{M}nk} . \quad (1)$$

The matrix expression of equation (1) is given as follows:

$$\begin{bmatrix} S(0) \\ \vdots \\ S(M-1) \end{bmatrix} = \boldsymbol{D}_M \begin{bmatrix} s(0) \\ \vdots \\ s(M-1) \end{bmatrix}, \quad (2)$$

where $\boldsymbol{D}_M$ is M x M square matrix and is given by

$$\boldsymbol{D}_M = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{-j\frac{2\pi\times1\times1}{M}} & \cdots & e^{-j\frac{2\pi\times1\times(M-1)}{M}} \\ \vdots & \vdots & & \vdots \\ 1 & e^{-j\frac{2\pi(M-1)\times1}{M}} & \cdots & e^{-j\frac{2\pi(M-1)\times(M-1)}{M}} \end{bmatrix}, \quad (3)$$

Note that D_M performs M point DFT spreading to convert the time domain signal, $s(n)$ (n=0~M-1) to the frequency domain signal, $S(k)$ (k=0~M-1). $S(0)$~$S(M-1)$ are fed to N point IFFT processor, where N is power of two. IFFT converts the frequency domain signals, $S(0)$~$S(M-1)$ to the time domain signals, $T(n)$ (n=0~N-1), as shown below:

$$\begin{bmatrix} T(0) \\ \vdots \\ T(N-1) \end{bmatrix} = \frac{1}{N} \boldsymbol{D}_N{}^H \begin{bmatrix} 0 \\ S(0) \\ \vdots \\ S(M/2-1) \\ 0 \\ \vdots \\ 0 \\ S(M/2) \\ \vdots \\ S(M-1) \end{bmatrix}, \quad (4)$$

where $(\ )^{H}$ is the complex conjugate of the transpose matrix and $\boldsymbol{D}_N$ is N x N square matrix, which is given by:

$$\boldsymbol{D}_N = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{-j\frac{2\pi\times1\times1}{N}} & \cdots & e^{-j\frac{2\pi\times1\times(N-1)}{N}} \\ \vdots & \vdots & & \vdots \\ 1 & e^{-j\frac{2\pi(N-1)\times1}{N}} & \cdots & e^{-j\frac{2\pi(N-1)\times(N-1)}{N}} \end{bmatrix}. \quad (5)$$

The multiplication of $\boldsymbol{D}_N{}^{H}$ means IFFT processing. After IFFT, CP is added and transmitted like the conventional DFTs-OFDM.

Note that zero is inserted at the first row of the input of FFT processor as shown in equation (4). This means the DC sub-carrier is made null. The frequency domain signals are split into two parts, i.e., $S(0)$~$S(M/2-1)$ and $S(M/2)$~$S(M-1)$. Therefore, the output of IFFT processor is not a pure single carrier modulation signal and DC component, $S(0)$ is transmitted via sub-carrier with frequency=$1/N$ instead of frequency=0. Thus, PAPR could be slightly larger than that of the conventional DFTs-OFDM.

Let us consider the receiver side next. Supposing that the complex envelop of the received signal at the FFT processor input is $g(n)$ (n=0~N-1), the output of FFT processor, $G(k)$ (k=0~N-1) is given by:

$$\begin{bmatrix} G(0) \\ \vdots \\ G(N-1) \end{bmatrix} = \boldsymbol{D}_N \begin{bmatrix} g(0) \\ \vdots \\ g(N-1) \end{bmatrix}, \quad (6)$$

where $\boldsymbol{D}_N$ is given by equation (5). As $g(n)$ suffers frequency selective fading in mobile environments, frequency domain equalization (FDE) is performed to the frequency domain signals, $G(k)$. Supposing that $E(k)$ (k=0~N-1) is the equalization coefficient for linear FDE, the output of FDE, $R(k)$ (k=0~N-1) is given by:

$$\begin{bmatrix} R(0) \\ \vdots \\ R(N-1) \end{bmatrix} = \begin{bmatrix} E(0)\cdot G(0) \\ \vdots \\ E(N-1)\cdot G(N-1) \end{bmatrix}. \quad (7)$$

After FDE, $R(0)$ is discarded because DC sub-carrier is not used and is made null at the transmitter in the proposed NDCS-DFTs-OFDM.

Then, the upper part signals, $R(1)$ to $R(M/2)$ and the lower part signals, $R(N-M/2)$ to $R(N-1)$ are put into the M point IDFT processor to convert them to the time domain signals, $r(n)$ (n=0~M-1), which is given by:

$$\begin{bmatrix} r(0) \\ \vdots \\ r(M-1) \end{bmatrix} = \frac{1}{M} \boldsymbol{D}_M{}^H \begin{bmatrix} R(1) \\ \vdots \\ R(M/2) \\ R(N-M/2) \\ \vdots \\ R(N-1) \end{bmatrix}, \quad (8)$$

where $\boldsymbol{D}_M{}^{H}$ is the complex conjugate of the transpose matrix of $\boldsymbol{D}_M$. The reconstructed signal, $r(n)$ is never affected by DC offset error between AD converters and I/Q demodulator, like OFDM signals of IEEE802.11a, for example.

C. Application of DFT spreading to OFDM-based WLAN

As shown in Fig. 1 (a), all of the functional blocks except M point DFT processor in the NDCS-DFTs-OFDM transmitter are included in IEEE802.11n/ac OFDM transmitter. Furthermore, as shown in Fig. 1(b), all of the functional blocks except M point IDFT processor in the NDCS-DFTs-OFDM receiver are also included in IEEE802.11n/ac OFDM receiver. Furthermore, all of the sub-carriers used in the proposed NDCS-DFTs-OFDM are exactly the same as those of conventional IEEE802.11n/ac, thus the preamble format used in IEEE802.11n/ac WLAN can be re-used and do not need to be changed at all. In addition, we can expect the same robustness against DC offset error as IEEE802.11n/ac OFDM.

D. Additional signal processing complexity

Additional signal processing complexity needs to be evaluated when the proposed NDCS-DFTs-OFDM is applied to OFDM based WLAN. Signal processing complexity of NDCS-DFTs-OFDM is essentially the same as that of conventional DFTs-OFDM. If M is power of two, we can employ FFT algorithm to reduce the number of complex multiplication for DFT. However, when we assume the existing parameters of IEEE802.11n/ac WLAN, the number of sub-carriers, M is 56 and the FFT size, N is 64 for 20MHz band operation of IEEE802.11n/ac. Table I shows the comparison of signal processing complexity by the number of complex multiplications of NDCS-DFTs-OFDM and OFDM. FFT algorithm can reduce 64^2 complex multiplications to 192 for 64 points DFT. On the other hand, PFA (Prime Factor FFT algorithm) can be applied for 56 points DFT to reduce the signal processing complexity [7]. PFA can reduce 56^2 complex multiplications to 476 for 56 points DFT. Therefore, the total number of complex multiplications required for NDCS-DFTs-OFDM is 668 at the transmitter as shown in Table I. The signal processing complexity of NDCS-DFTs-OFDM is about 3.5 times larger

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than that of OFDM. This is a trade-off issue between the additional power consumption for DFT spreading in NDCS-DFTs-OFDM and the power consumption due to large OBO of HPA in OFDM. Considering that Moore's law is still effective, NDCS-DFTs-OFDM seems promising to improve energy efficiency of OFDM based WLAN in near future.

In IEEE802.11ah using UHF band, 1/10 clock down operation of IEEE802.11ac OFDM is proposed. In this case, power consumption of OFDM modem is essentially 1/10 compared with that of IEEE802.11n/ac and additional signal processing complexity will not be a significant problem. Therefore, NDCS-DFTs-OFDM will be useful for energy efficiency improvement.

III. Performance Evaluation

A. Simulation parameters

PAPR, power spectrum, BER performance and EVM of NDCS-DFTs-OFDM are evaluated by computer simulation and are compared with those of OFDM and DFTs-OFDM. Major simulation parameters are shown in Table II, where the number of sub-carriers and FFT/IFFT size are the same as those of IEEE802.11n/ac standard. BER performance is evaluated in AWGN (Additive White Gaussian Noise) channel to demonstrate its robustness to DC offset error.

B. PAPR

Fig. 2 (a) shows CCDF (Complementary Cumulative Distribution Function) of PAPR of the proposed NDCS-DFTs-OFDM and compares it with those of the conventional OFDM and DFTs-OFDM in the case of QPSK. As DFTs-OFDM is essentially the same as single carrier modulation signals filtered by the ideal filter, its PAPR is the least among three schemes, and is 2dB lower than that of OFDM at CCDF=1%. PAPR of the proposed NDCS-DFTs-OFDM is slightly higher than that of DFTs-OFDM, however it is 1.7dB lower than that of OFDM. Fig. 2 (b) compares CCDF of PAPR of the proposed NDCS-DFTs-OFDM with DFTs-OFDM and OFDM in the case of 16QAM. PAPR of NDCS-DFTs-OFDM is slightly higher that that of DFTs-OFDM, however it is 1.2dB lower that that of OFDM. These results confirm that the proposed NDCS-DFTs-OFDM scheme achieves as low PAPR as DFTs-OFDM.

C. Power spectrum

Fig. 3 shows power spectrum of NDCS-DFTs-OFDM in the case of QPSK and compares it with DFTs-OFDM and OFDM in the case of linear amplifier and non-linear amplifier with OBO=3dB. Rapp model is used for the simulation of non-linear amplifier. As seen in Fig. 3 (a), there is no difference among three schemes in a linear channel. Note that DFTs-OFDM has slightly narrower spectrum as DC sub-carrier is used. In the case of non-linear amplifier with OBO=3dB as shown in Fig. 3 (b), the side-lobe level of DFTs-OFDM signals is the least among three schemes. The side-lobe level of NDCS-DFTs-OFDM is almost the same as that of DFTs-OFDM and a few dB lower than that of OFDM. This means the proposed scheme has lower adjacent channel power leakage than OFDM when OBO is 3dB and can use smaller OBO than OFDM.

D. Power spectrum

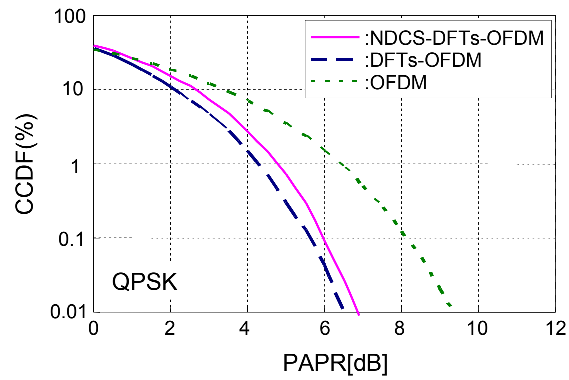
Fig. 3 shows power spectrum of NDCS-DFTs-OFDM in the case of QPSK and compares it with DFTs-OFDM and

TABLE I. Signal processing complexity in terms of the number of complex multiplications at the transmitter

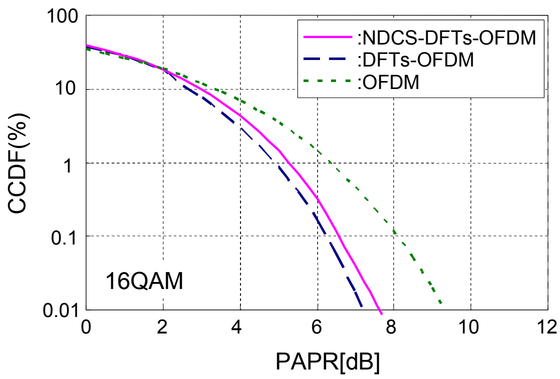
	DFT spreading (56 point)	IFFT (64 point)	Total
OFDM	0	192	192
NDCS-DFTs-OFDM DFTs-OFDM	476	192	668

TABLE II. Major Simulation Parameters.

Number of sub-carriers	56
FFT/IFFT size	64
Modulation scheme	QPSK/16QAM/64QAM
FEC	Convolutional-coding−Viterbi-decoding, R=3/4 or R=1/2



(a) QPSK



(b) 16QAM

Figure 2. PAPR comparison of NDCS-DFTs-OFDM, DFTs-OFDM and OFDM.

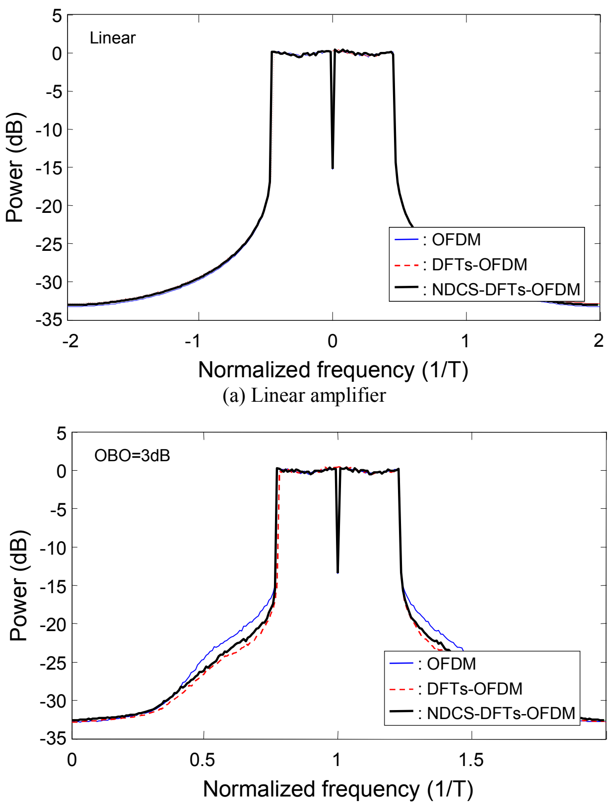
OFDM in the case of linear amplifier and non-linear amplifier with OBO=3dB. Rapp model is used for the simulation of non-linear amplifier [8]. As seen in Fig. 3 (a), there is no difference among three schemes in a linear channel. Note that DFTs-OFDM has slightly narrower spectrum as DC sub-carrier is used. In the case of non-linear amplifier with OBO=3dB as shown in Fig. 3 (b), the side-lobe level of DFTs-OFDM signals is the least among three schemes. The side-lobe level of NDCS-DFTs-OFDM is almost the same as that of DFTs-OFDM and a few dB lower than that of OFDM. This means the proposed scheme has lower adjacent channel power leakage than OFDM when OBO is 3dB and can use smaller OBO than OFDM.

E. BER performance and EVM

Fig. 4 compares BER performance of NDCS-DFTs-OFDM and DFTs-OFDM using QPSK with/without R=3/4 FEC, when DC offset error is 5%. DC offset error is defined by ΔA/A at the D/A converter of the transmitter and the A/D converter of the receiver where ΔA is DC offset error and A is the eye aperture at I/Q channels. When DC offset error exists, NDCS-DFTs-OFDM shows no E_b/N_o degradation and less E_b/N_o degradation at BER=10^{-4} in comparison with DFTs-OFDM.

Fig. 5 compares E_b/N_o degradation of NDCS-DFTs-OFDM and DFTs-OFDM as a function of DC offset error at BER=10^{-4}, where QPSK and 16QAM with/without R=1/2 FEC are employed for performance evaluation. Large E_b/N_o degradation due to DC offset error is observed in DFTs-OFDM. Though E_b/N_o degradation at BER=10^{-4} is as large as 3dB for 16QAM without FEC and 1dB for 16QAM with FEC in DFTs-OFDM, NDCS-DFTs-OFDM shows no E_b/N_o degradation due to DC offset error.

Another measure to evaluate the robustness against DC offset error is EVM. Fig. 6 compares EVM of QPSK,



(a) Linear amplifier

(b) Non-linear amplifier with OBO=3dB.

Figure 3. Power spectrum comparison of NDCS-DFTs-OFDM, DFTs-OFDM and OFDM

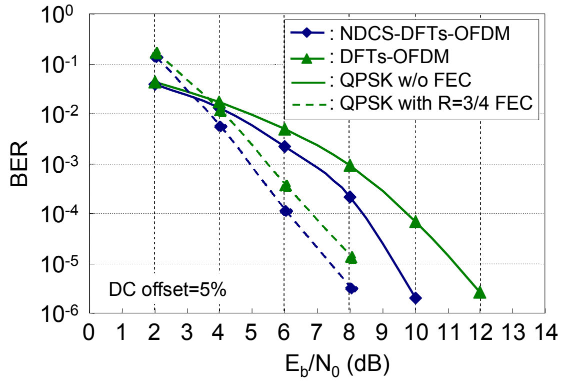


Figure 4. BER performance of NDCS-DFTs-OFDM and DFTs-OFDM when DC offset error=5%.

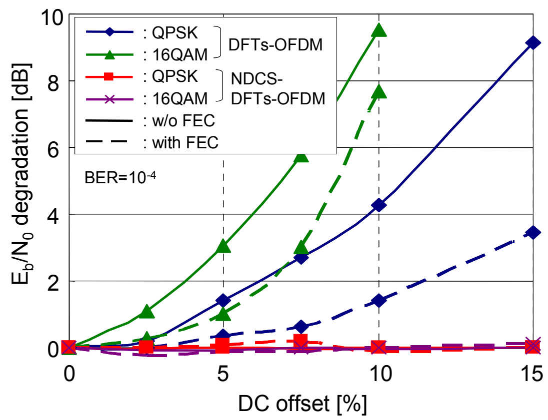


Figure 5. E_b/N_o degradation as a function of DC offset error in NDCS-DFTs-OFDM and DFTs-OFDM.

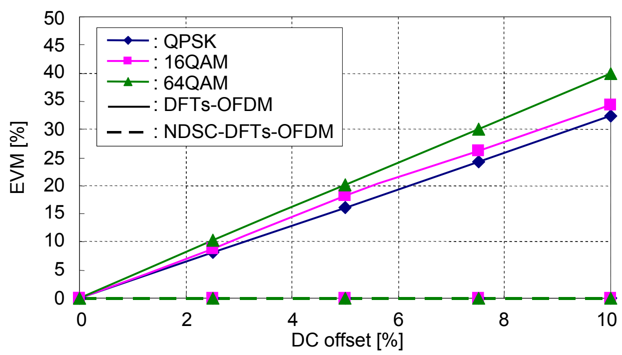


Figure 6. EVM as a function of DC offset error in NDCS-DFTs-OFDM and DFTs-OFDM.

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16QAM and 64QAM as a function of DC offset error for NDCS-DFTs-OFDM and DFTs-OFDM. As shown there, EVM increases in proportion to DC offset error in DFTs-OFDM. EVM of 16QAM and 64QAM is slightly worse than that of QPSK. On the other hand, no EVM increase is shown according to DC offset error in NDCS-DFTs-OFDM, Therefore, BER performance of NDCS-DFTs-OFDM is not degraded due to DC offset error as shown in Fig. 4 and Fig. 5.

IV. CONCLUSIONS

This paper described an application of DFT spreading to OFDM based WLAN to improve energy efficiency. In order to maintain the robustness to DC offset error, this paper proposed a new type of DFTs-OFDM, NDCS-DFTs-OFDM by splitting the spectrum after DFT spreading into two parts and making DC sub-carrier null. Though the signal processing complexity is 3.5 times larger than OFDM under the condition that the basic parameters of OFDM are maintained, the simulation results confirmed the proposed NDCS-DFTs-OFDM achieves both advantages of low PAPR and robustness to DC offset error. Future work includes BER performance evaluation of NDCS-DFTs-OFDM in frequency selective fading as well as under the non-linear amplifier operation. In addition, the power consumption trade-off between NDCS-DFTs-OFDM and larger OBO of HPA must be conducted.

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