Comparison of DCT and Wavelet Based OFDM System Working in 60 GHz Band

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Abstract

At the 60 GHz band a massive amount of spectral space (5 GHz) has been allocated unlicensed worldwide for dense wireless local communications. OFDM has gained much popularity in the field of wireless communication because of its ability to transfer the data at higher rate, high bandwidth efficiency and robustness to multipath and delay.The BER performance of conventional FFT-OFDM system is compared with DWT-OFDM system and DCT-OFDM system in an AWGN environment and Saleh-Valenzuela (SV) channel model at 60 GHz. Several wavelets such as Haar, Daubechies, Symlet, biorthogonal are considered. The BER is calculated for signaling format BPSK and the performance is analyzed at 60 GHz.Simulation results show that DCT based scheme yields the lowest average bit error rate. While out of all wavelet mother used Haar and Daubechies wavelet based scheme yields lower BER than FFT-OFDM for an AWGN channel. Whereas SV channel model working at 60 GHz FFT-OFDM performs best amongst the three.

Keywords: *bit error rate (BER), orthogonal frequency-division multiplexing (OFDM), Fourier-based OFDM (FFT-OFDM), discrete cosine transform (DCT), discrete cosine based OFDM (DCT-OFDM), Discrete Wavelet Transform (DWT), discrete wavelet based OFDM (DWT-OFDM)*

1. Introduction

There has been a huge rise in the demand for flexible high data-rate services. The broadband wireless services which require high data-rates and high signal quality depend a lot on the wireless channels. Besides, the wireless channels have impairment such as fading, shadowing and multi-user interference which highly degrade the system performance. OFDM (orthogonal frequency-division multiplexing) is a modulation technique which allocates orthogonal sub carriers. OFDM is a special case of multicarrier transmission, where a single data stream is transmitted over a number of lower-rate subcarriers (SCs). Also OFDM is robust against narrowband interference because such interference affects only a small percentage of the subcarriers increasing robustness against frequency-selective fading.

OFDM is used in physical layer of various wireless standards such as IEEE 802.11a, IEEE 802.16a, and HIPERLAN/2, DAB, DVB. All these commercially used schemes use discrete Fourier transform to generate orthogonal subcarriers. These systems use complex exponential functions set as orthogonal basis. However, the complex exponential function set is not the only orthogonal basis that can be used to construct baseband multicarrier signals. A single set of cosinusoidal functions can be used as an orthogonal basis to implement the multicarrier modulation scheme, and this scheme can be synthesized using a discrete cosine transform (DCT). Although the wavelets are widely used in signal processing, few wavelets applications are known in data transmission. Much research suggests wavelet OFDM implementation provides performance gains over Fourier based OFDM, due to superior spectral containment properties of wavelet filters. By using the transform, the spectral containment of the channels is better since it does not use cyclic prefix [13-16]. Hence, the DCT based OFDM scheme is denoted as DCT-OFDM, wavelet based OFDM is denoted as DWT-OFDM and the conventional OFDM system is denoted as DFT-OFDM in this paper.

Recent developments in wireless communications are being driven primarily by the increased demands for radio bandwidth. The 60 GHz band have a massive amount of spectral space (5 GHz), which has been allocated worldwide for dense wireless local communications. At this frequency band the specific attenuation due to atmospheric oxygen is 10–15 dB/km, (precisely 14.7 dB at 60 GHz) which makes the 60 GHz band unsuitable for long-range (> 2 km). For indoor environment distance is considered less than 50 m, therefore 10-15 dB/km attenuation does not carry much significant impact on the performance of communication system working in this band. Thus, there is 6 GHz (58 to 64 GHz) bandwidth available with specific attenuation in excess of 10 dB. The major reason for the interest in 60 GHz band is the huge unlicensed bandwidth. The range of unlicensed frequencies available is different in each country. This makes the 60 GHz band of utmost interest for all kinds of short-range wireless communications [19].

The purpose of this paper is to compare the performance of Fourier based OFDM with DCT-OFDM and wavelet based OFDM for different wavelets. The channel models used are AWGN channel and indoor multipath channel working at 60 GHz. At 60 GHz band channel model used is a generic channel model that considers clustering. This model is based on the extension of the Saleh–Valenzuela (SV) model.

2. Conventional OFDM System: FFT-OFDM

To generate OFDM successfully the relationship between all the carriers must be carefully controlled to maintain the orthogonality of the carriers. For this reason, OFDM is generated by firstly choosing the spectrum required, based on the input data, and modulation scheme used. Each carrier to be produced is assigned some data to transmit. The required amplitude and phase of the carrier is then calculated based on the modulation scheme (typically differential BPSK, QPSK, or QAM).

The multiple orthogonal subcarrier signals, which are overlapped in spectrum mathematically resemble to N-point IDFT of the transmitted symbols. In practice, DFT and IDFT processes are useful for implementing these orthogonal signals. So to generate an OFDM symbol IDFT of modulated signal is computed. DFT and IDFT can be implemented efficiently by using fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT), respectively. To generate orthogonal sub-carriers N-point IFFT is taken for the transmitted symbols so as to generate, the samples for the sum of N orthogonal subcarrier signals. Thus an OFDM symbol is generated by computing the IDFT of the complex modulation symbols to be conveyed in each sub-channel,

The receiver will receive a sample corrupted by additive noise. Taking the N-point FFT of the received samples the noisy version of transmitted symbols can be obtained in the receiver. The spectrum of the OFDM signal can be considered as the sum of the frequency shifted sinc functions in the frequency domain because all subcarriers are of the finite duration. The OFDM scheme also inserts a guard interval in the time domain, called cyclic prefix (CP), which mitigates the inter-symbol interference (ISI) between OFDM symbols.

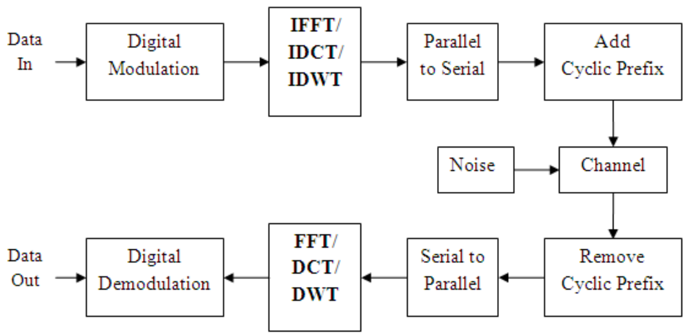

Fig 1: Generic OFDM System Transmitter and Receiver

Figure 1 shows the configuration for a basic OFDM transmitter and receiver. The signal generated is at baseband and so to generate an RF signal the signal must be filtered and mixed to the desired transmission frequency.

The sequence of N complex numbers $x_0 \ldots x_{N-1}$ is transformed into the sequence of N complex numbers $X_0 \ldots X_{N-1}$ by the DFT according to the Eq. (1)

$$X_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n e^{\frac{-2\pi j}{N}kn}, k = 0, \ldots N-1 \qquad --- \quad (1)$$

where i is the imaginary unit and $e^{\dagger}(2(i/N)$ is a primitive N^{th} root of unity and $k = 0, \ldots, N-1$. The Inverse Discrete Fourier Transform (IDFT) is given by Eq. (2)

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{-j\frac{2\pi kn}{N}} \quad n = 0, \ldots N-1 \qquad --- \quad (2)$$

Where $n = 0 \ldots N-1$

The complex numbers X_k represent the amplitude and phase of the different sinusoidal components of the input signal x_n. The DFT computes the X_k from the x_n, while the IDFT shows how to compute the x_n as a sum of sinusoidal components $\left(\frac{1}{N}\right) X_k e^{-\frac{2\pi i}{N}kn}$ with frequency $\frac{k}{N}$ cycles per sample.

The DFT can be computed efficiently in practice using a Fast Fourier Transform (FFT) algorithm. "DFT" refers to a mathematical transformation or function, regardless of how it is computed, whereas "FFT" refers to a specific family of algorithms for computing DFTs.

To maintain the orthogonality during channel transmission cyclic prefix is added to OFDM frame which must be longer than the channel impulse response. Channel performance can be estimated and hence equalized by inserting pilot sub-carriers at predefined sub-carrier intervals.

3. DCT Based OFDM System: DCT-OFDM

Instead of using complex exponential functions, cosinusoidal functions can be used as orthogonal basis to implement multi-carrier scheme. This can be synthesized using discrete cosine transform (DCT) [8]. For fast implementation algorithms DCT can provide fewer computational steps than FFT based OFDM [6], [7]. The effect of carrier frequency offset (CFO) will introduce inter-carrier-interference (ICI) in both the DFT-OFDM and DCT-OFDM [9].

A single cosinusoidal functions set $\cos(2\pi n F_\Delta t)$ will be used as the orthogonal basis to implement MCM in DCT-OFDM. The minimum F_Δ required to satisfy Eq. (3) is 1/2T Hz.

$$\int_0^T \sqrt{\frac{2}{T}}\cos(2\pi F_\Delta t)\sqrt{\frac{2}{T}}\cos(2\pi m F_\Delta t)\,dt = \begin{cases}1, & k = m\\ 0, & k \neq m\end{cases} \qquad ---(3)$$

The continuous-time output signal of a DCT based OFDM system can be written as

$$X(t) = \sqrt{\frac{2}{N_s}}\sum_{n=0}^{N_s-1} d_n \beta_n \cos\left(\frac{n\pi t}{T_s}\right) \qquad ---(4)$$

Where $d_0, d_1 \ldots\ldots D_{Ns-1}$ are N_s independent data symbols obtained from a modulation constellation and

$$\beta_n = \begin{cases} \frac{1}{\sqrt{2}}, & n = 0\\ 1, & n = 1,2,\ldots,N_S - 1\end{cases} \qquad ---(5)$$

The BER performance of DCT-OFDM is better than DFT-OFDM, the signal energy in DCT is concentrated in a few low-index DCT coefficients, while the remaining coefficients are zero or are negligibly small. Also it has been shown that the DCT is close to optimal in terms of energy-compaction capabilities. [11]

A zero-padding guard-interval scheme is used in DCT-OFDM system. The zero-padding scheme will eliminate ISI, and also improve transmission efficiency. In DFT-OFDM was reported in [10], where it was shown that the zero-padded (ZP) DFT-OFDM can achieve a better BER performance than cyclic prefix (CP) DFT-OFDM.

4. Wavelet Based OFDM System: DWT-OFDM

This section discusses the alternative way to implement OFDM using DWT. In Wavelet based OFDM (DWT-OFDM), the time-windowed complex exponentials are replaced by wavelet “carriers", at different scales *(j)* and positions on the time axis *(k).* These functions are generated by the translation and dilation of a unique function, called "wavelets mother" and denoted by $\psi(t)$:

$$\psi_{j,k}(t) = 2^{-j/2}\,\psi(2^{-j}t - k) \qquad --- (6)$$

The orthogonality of these carriers relies on time location *(k)* and scale index *(j)*. Wavelet carriers exhibit better time-frequency localization than complex exponentials [12] while DWT-OFDM implementation complexity is comparable to that of FFT- OFDM. The key point ‘orthogonality’ is achieved by generating members of a wavelet family, according to Eq. (6)

$$\langle \psi_{j,k}(t), \psi_{m,n}(t) \rangle = \begin{cases} 1, \text{ if } j = m \text{ and } k = n \\ 0, \text{ otherwise} \end{cases} \qquad --- (7)$$

These functions have orthonormal basis of $L^2(R)$, if infinite number of scales $j \in Z$ are considered. To obtain finite number of scales, scaling function $\varphi(t)$ is used. DWT-OFDM symbol now can be considered as weighted sum of wavelet and scale carriers, as expressed in Eq. (7), which is close to the Inverse Wavelet Transform (IDWT).

$$s(t) = \sum_{j \le J}\sum_{k} w_{j,k}(t)\psi_{j,k}(t) + \sum_{k} a_{J,k}\,\varphi_{J,k}(t) \qquad --- (8)$$

The data symbols are seen by IDWT modulator as sequence of wavelet $w_{j,k}$ and approximation coefficients $a_{J,k}$. According to Eq. (6) *J* is the scale with poorest time resolution and best frequency localization of the carriers. For computing IDWT, Mallat’s algorithm based on filter bank is used instead of Eq. (8). At the output of the filter discrete version of DWT-OFDM symbol is obtained, with impulse response of filters (low-pass and high-pass) decided by the wavelet mother.

5. 60 GHz Channel characterization and Modeling

In context to 60 GHz an indoor channel model is considered. The cluster model based on Saleh- Valenzuela (SV) model is used. The 60 GHz wave exhibit strong atmospheric oxygen absorption (about 15dB/km) and high reflection. Figure 2 shows the attenuation by oxygen and uncondensed water vapor as a function of frequency. This high attenuation of the 60 GHz waves implies that cell radius will be few kilometers outdoor. In an indoor environment, the cell will be limited to a single room. Additionally concrete walls contribute to attenuation by 20 dB; this avoids interference with neighboring cells. For an electromagnetic wave everything which is larger than half the wavelength absorbs most of the power in the given direction and reflects the remaining. For 60 GHz wavelength is 5 mm, hence every object larger than 2.5 mm is an obstacle. To compensate atmospheric loss and reflection loss antennas with higher gain can be used. The influence of multipath interference can be reduced with use of narrow beamwidth antenna instead of omnidirectional antenna. But to provide better flexibility and link adaptability facilitating point-to-multipoint communications, moderate-directivity antennas or omnidirectional antennas are simple solutions for 60 GHz wireless systems. [24]

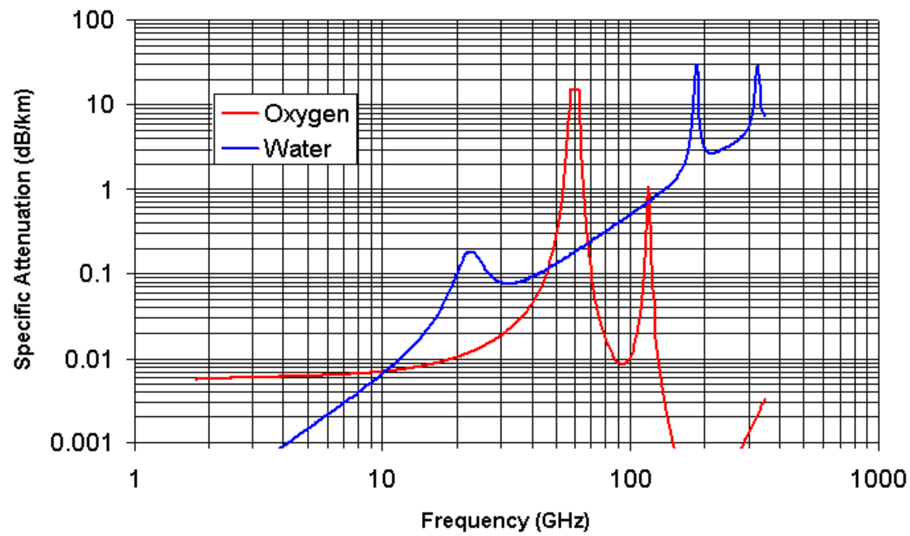

Fig 2: Specific attenuation for atmospheric Oxygen and Water Vapor [21]

SV Channel Model:

The Saleh-Valenzuela (SV) model [23] is the typical empirical model for indoor environments. It is commonly used to describe indoor propagation channel impulse responses. The basic assumption with this model is that multipath components (MPCs) arrive to the receiver in concentrated groups; known as clusters. These clusters are formed by the multiple reflections from the objects in the vicinity of receiver and transmitter. The clusters, as well as the rays within a cluster, arrive according to Poisson processes with different rates and have inter-arrival times that are exponentially distributed. The MPCs amplitudes are independent Rayleigh random variables and the corresponding phase angles are independent uniform random variables over. The power decays exponentially for clusters and MPCs within a cluster. A typical power delay profile based on the model is shown in Figure 3. The impulse response of the channel is given by

$$\boldsymbol{h}(t) = \sum_{l=1}^{\infty}\sum_{k=1}^{\infty} \beta_{kl}\, e^{j\theta_{kl}} \delta(t - T_l - \tau_{kl}) \qquad --- (9)$$

Where T_l is the arrival time of the l^{th} cluster, τ_{kl} is the arrival time of the k^{th} ray measured from the beginning of the l^{th} cluster, while β_{kl} and θ_{kl} are the gain and phase of the k^{th} ray of the l^{th} cluster. The mean square values of the gain are given by

$$\overline{\beta_{kl}^2} \equiv \overline{\beta^2(T_l, \tau_{kl})} = \overline{\beta^2(0,0)}e^{-T_l/\Gamma}e^{-\tau_{kl}/\gamma} \qquad ---(10)$$

Where $\beta^2(0,0)$ is the average power gain of the first ray of the first cluster, and $\tilde{A}$ and $\tilde{a}$ are the cluster and ray power delay constants, respectively. T_l and τ_{kl} are described by the independent inter-arrival exponential probability density functions

$$p(T_l|T_{l-1}) = \Lambda exp[-\Lambda(T_l - T_{l-1})]$$

$$p(\tau_{kl}|\tau_{(k-1)l}) = \lambda exp[-\lambda(\tau_{kl} - \tau_{(k-1)l})] \qquad ---(11)$$

The mean number of clusters for various scenarios and environments does not follow a specific distribution. The observed mean numbers of clusters are decided by measurement bandwidth and number of objects responsible for scattering. Channel parameters from IEEE 802.15.3c channel model are used. [22]

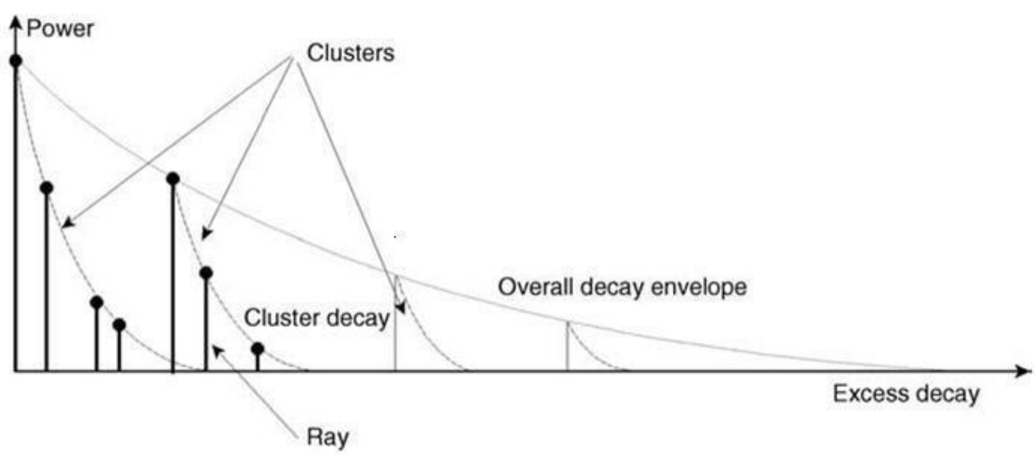

Fig 3: A typical power delay profile based on the Saleh-Valenzuela model

Analysis of IEEE 802.15.3c measurement data for various environments and scenarios shows that mean number of clusters does not follow a specific distribution. However, the observed mean number of clusters can be calculated by visual inspection. Channel parameters from IEEE 802.15.3c channel model are used for simulation purpose. [22]. The channel parameters were considered for various indoor scenarios such as residential, office where residential indoor environment is characterized with indoor walls of reasonable thickness while offices contain furniture, long corridors and office partitioning.

6. Simulation

Simulations Parameters: The system replicated SV channel model which describes the typical indoor transmission environment at 60 GHz. Channel parameters from IEEE 802.15.3c channel model at 60 GHz are used. The numbers of subcarriers used in OFDM system are 256, and the length of the zero-padding guard interval is 64. All of the simulations assume that, channel-state information will not change in one OFDM symbol. The system simulated does not use any channel estimation technique and error estimation or correction capabilities. BPSK modulation scheme is used. BER performance for FFT-OFDM, DCT-OFDM and DWT-OFDM is evaluated. For DWT-OFDM r different wavelet mothers namely Haar, Daubechies (dB2), Symlets (sym2), Coiflet (coifi2) and Bi-orthogonal were used. The DWT-OFDM families do not require cyclic prefix due to the overlapping nature of their properties. The simulation is carried out for two channel models namely AWGN channel and SV channel model operating at 60 GHz.

Results: Simulation is carried out for SNR in the range 0 to 40dB, for BPSK as a modulation technique, the BER of DCT-OFDM to zero above 5dB of SNR. DWT-OFDM performance is strongly decided by 'mother wavelet'. Out of all wavelet families chosen for simulation the Daubechies' family (Haar and Bi-orthogonal) outperforms the FFT-OFDM as shown in Fig. 4. For other mother wavelets, namely Symlets (sym2), Coiflet (coifi2) and db2 a floor in BER is observed after SNR is more than 10 dB. Even though in the SNR range of 10 to 25 dB DWT-OFDM surpasses FFT-OFDM. For this simulation system no channel estimation technique is used.

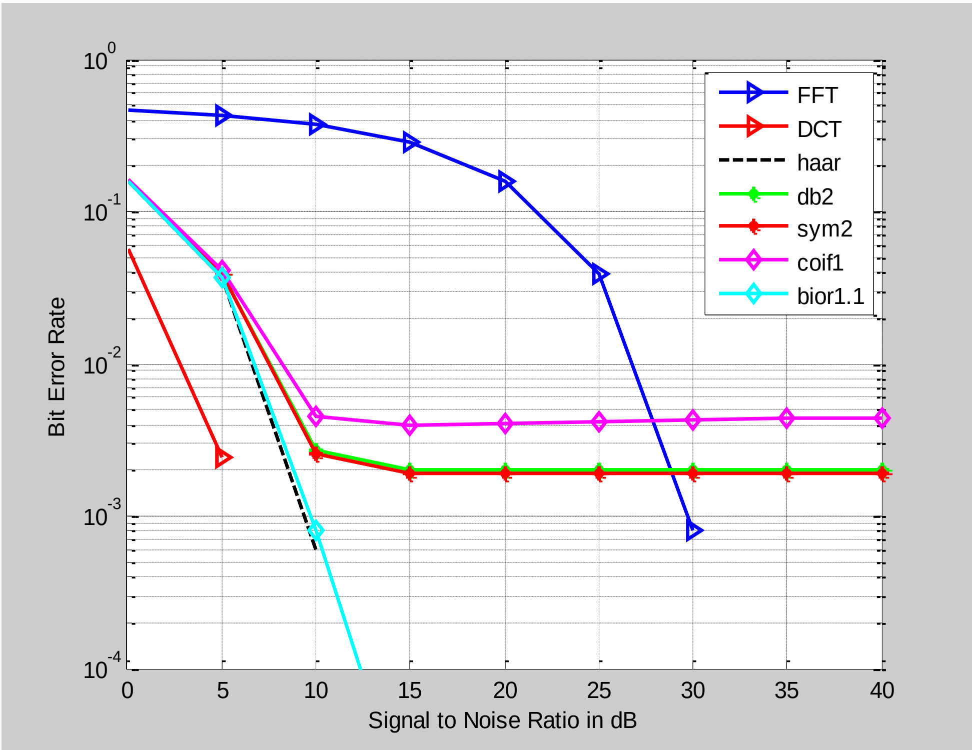

Fig 4: BER performance of FFT-OFDM, DCT-OFDM and DWT-OFDM for AWGN Channel

Same system is simulated at 60 GHz using SV channel model and various indoor scenarios were considered. It had been observed that change in the indoor scenario has relatively less effect on the BER of an OFDM scheme. For SV channel model a threshold of 20 dB below the strongest path is used so that paths arrived below this threshold are neglected and set to zero. This is to consider only the effective paths to be used for the channel modeling. For 60 GHz and

SV channel model simulation results indicated in Figure 4 show that FFT-OFDM system performances better than DCT-OFDM and DWT OFDM system.

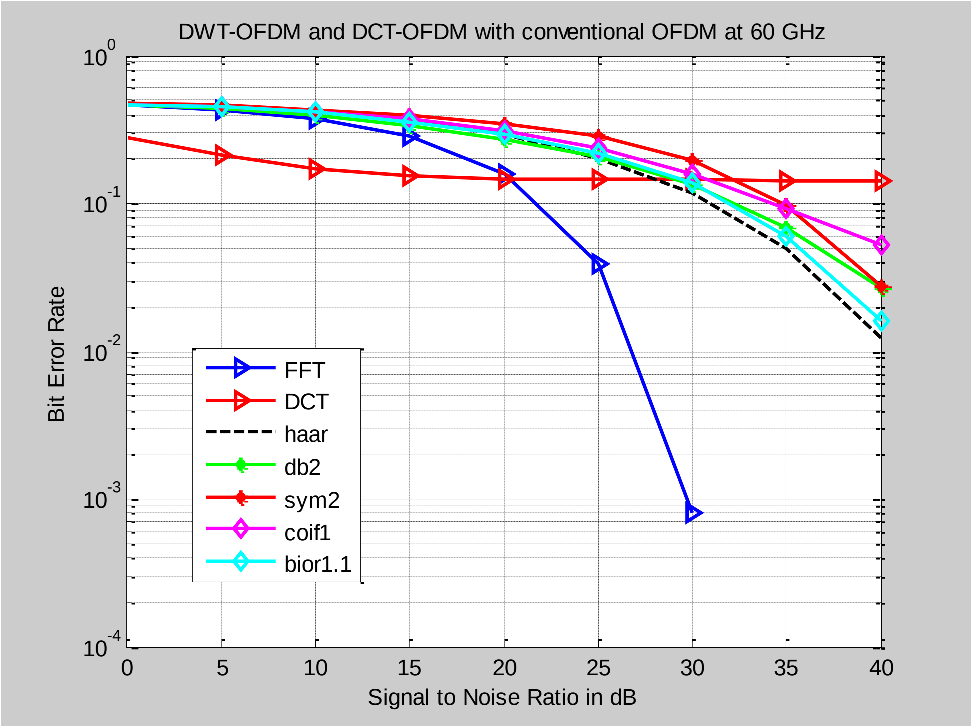

Fig 5: BER performance of FFT-OFDM, DCT-OFDM and DWT-OFDM at 60 GHz

7. Conclusions

Simulation results show that DCT based scheme yields the lowest average bit error rate for AWGN channel. Whereas, out of all mother wavelets used Haar and Daubechies wavelet based scheme yields lower BER than FFT-OFDM for an AWGN channel. In case of an OFDM communication system at 60 GHz, it is observed that the performance of DCT-OFDM is excellent than the system using FFT and DWT.

The second experiment is performed for indoor SV model indicates diverse results as compared to AWGN channel model. In case of DWT-OFDM using AWGN Symlets (sym2), Coiflet (coifi2) and db2 result in constant BER after 10 dB SNR, whereas for SV model these perform almost same up to 40 dB SNR. Out of all five mother wavelets 'Haar' is the winner. In case of SV model FFT based system is the winner and DCT based system results in a worst selection.

Although the theory of wavelet transform has been well-evolved and documented over the past years, the use of wavelets in the communication systems is still in the early stage of the development. Future work may include the implementation of forward error correction techniques such as convolution codes. An efficient channel estimation algorithm may be included for performance evaluation of DCT-OFDM and DWT-OFDM working at 60 GHz band.

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