Towards a Seamless Future Generation Network for High Speed Wireless Communications[*]

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Abstract—**The MIMO technology towards achieving future generation broadband networks design criteria is presented. Typical next generation scenarios are investigated. The MIMO technology is integrated with the OFDM technology for effective space, time and frequency diversity exploitations for high speed outdoor environment. Two different OFDM design kernels (fast Fourier transform (FFT) and wavelet packet transform (WPT)) are used at the baseband for OFDM system travelling at terrestrial high speed for 800MHz and 2.6GHz operating frequencies. Results show that the wavelet kernel for designing OFDM systems can withstand doubly selective channel fading for mobiles speeds up to 280Km/hr at the expense of the traditional OFDM design kernel, the fast Fourier transform.**

Keywords—Doppler Effect; Doubly selective fading; frequency-selective fading; OFDM; Wavelet; MIMO

I. INTRODUCTION

The broadband network for next generation communications is a multiple input multiple output (MIMO) network [1-3] defined around 2x2, 4x2 and 4x4 MIMO systems such as the long-term evolution (LTE) and LTE advanced [4]. It uses OFDM for the downlink [5, 6]. The broadband LTE-advanced Release 10, for instance, is now greatly being pursued for building more dependable seamless service and was earlier believed to offer stationary downlink (DL) data size of 1Gb/s and mobile data size of 100Mb/s in wireless communications [7], although it has been extended now to 3Gb/s DL in the subsequent Releases [8]. The air-interface of this technology adopts the OFDM since it can combat inter-symbol interference (ISI) and also converts the frequency selective channel into a flat-fading channel. Also, OFDM is the key air-interface in digital video broadcasting for –terrestrial (DVB-T) and –satellite (DVB-S) wireless communications. Thus, the broadband LTE-advanced uses MIMO-OFDM.

One of the most advocated methods of deploying multi-antenna systems in broadband technology involve the space-time coding [1, 2]. It is the MIMO standard for LTE-Advanced [9]. This is because STBC can exploit the space, time and frequency diversity gains. Most early space-time (ST) coding scheme discuss the case of a frequency-flat fading channel. In practice, the broadband wireless communication channel is frequency-selective and exhibit inter-symbol interference (ISI) that depletes the performance of the system [10]. For broadband wireless systems, the MIMO channels experience frequency-selective fading, which complicates the design of ST codes because of ISI [11].

This is usually addressed by the use of OFDM with MIMO, hence the MIMO-OFDM. The combination of MIMO and OFDM provides an attractive interface solution for next-generation wireless local area networks (WLANS), wireless metropolitan area networks (WMAN) and fourth generation mobile cellular wireless systems [12].

For instance MIMO technology provides two design advantages, namely spatial multiplexing which provides capacity gain, and space-time coding which improves link dependability through diversity gain [11, 12]. These advantages are usually exploited in the design of multi-antenna systems. Applying ST codes only separately over each frequency tone of the OFDM does not exploit frequency diversity. Thus, we choose to construct only space-time frequency (STF) codes that can exploit space, time and frequency diversities.

Broadband network users are necessarily non-stationary. The movement of the user relative to the transmitter cause the signals to fade depending on how fast the channel varies. This is usually discussed as time-selectively (in addition to the frequency-selectivity) which is the case of a moving receiver. STBC with OFDM can also be studied as space-frequency block codes (SFBC) [13, 14] or space-time frequency block codes (STFBC) [11] over frequency selective channels [15]. The SFBC provides spatial diversity gain only, which sometimes, can be achieved by forward error correction coding with interleaving [12].

The STFBC is preferred over SFBC since the former exploits space, time and frequency gains [10, 11] and the later exploits only space and frequency diversities but not time [10, 13, 14]. The advantage of combining MIMO and OFDM is that MIMO provides capacity and diversity gains while OFDM mitigates the deterring multipath effect. Like this study aims to establish, a high-speed mobile on railway wireless communication technology based on LTE has been discussed in [5] for traditional OFDM architecture. However, it will be shown that the traditional OFDM system is sub-optimal for high speed wireless communications.

In Section II, the OFDM design kernels are presented using the traditional FFT and wavelet transform while the channel system model is discussed in Section III including the Doppler effects. In Section IV, the simulation environment with results are discussed which including the single-input-single-out (SISO) and the MIMO channel, a typical representation of the broadband channel. The conclusion follows in Section V.

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II. Orthogonal Frequency Division Multiplexing

Orthogonal frequency division multiplexing (OFDM) divides wideband into many narrow-bands to increase the data rate. Traditionally kernel for designing OFDM is the FFT. Another kernel that provides signal representation half-way in time-frequency plane, the wavelet transform, is also discussed.

A. FFT-OFDM

OFDM system is used in baseband as modulation method that divides a selected bandwidth into smaller and many narrow bands. In time domain, an *N*-point FFT OFDM system can be represented as:

$$s[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{j2\pi nk/N}, \quad n = 0, 1, 2, \ldots, N-1 \qquad (1)$$

where $s[n]$ is the discrete form of $s(t)$, N is the number of sub-channels, $1/\sqrt{N}$ is a scaling factor with n as the index of the prevalent subcarrier. S_k is the QPSK mapped input symbol of kth sub-channel. The number of FFT points used is equivalent to the number of narrowband sub-channels over which the input symbols are multiplexed. Each of the resulting narrowband sub-channels is modulated by the mapped input bits. Cyclic prefix (CP) at least equal to the length of the channel response, L is pre-appended to each OFDM symbol to combat ISI. To account for the CP, Equation 1a can be modified as:

$$s[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{j2\pi nk/N}, \quad -N_g \le n \le N-1 \qquad (1b)$$

In Equation 1b, N_g denotes the length of CP pre-appended to every OFDM symbol.

B. Wavelet – OFDM

The discrete wavelet transform (DWT) can be used to study multicarrier systems as in [16]. It represents signals in time-frequency domain such that the signal exists neither purely in frequency domain nor purely in time domain. For a mapped input symbol S_k to be transformed by the DWT, the time domain output can be realized from [17];

$$s[n] = \sum_{k} \sum_{m=0}^{M-1} S_{k,n} \varphi_{m,n}(t) \qquad (2)$$

where $S_{k,n}$ represents the nth symbol which modulates the mth-waveform of the kth-constellation. $\varphi_{m,n}(t)$ represents the complex orthogonal DWT basis function similar to the traditional OFDM as:

$$\varphi_{m,n} = \begin{cases} 1 & n = m \\ 0 & elsewhere \end{cases} \qquad (3)$$

where m and n are scales and shifts respectively. If n is the index of each discrete wavelet symbol $s[n]$ of the continuous time symbol $s(t)$, then the wavelet transform is defined as [18]:

$$\psi_{k,a}(t) = e^{i\pi t^2} \qquad (4)$$

Now, let a continuous wavelet function be expressed as:

$$\psi_{k,a}(t) = \frac{1}{\sqrt{k}} \psi\left(\frac{t-a}{k}\right) \qquad (5)$$

where k and a are the scaling and shifting parameters respectively and $\psi(.)$ is called the mother wavelet. Then, from Equations 5 and 4 the resulting continuous transform can be represented as:

$$s_{CWT}(\tau,k) = \frac{1}{\sqrt{k}} \int_{-\infty}^{\infty} \exp\left[i\pi \frac{(t-\tau)^2}{k^2}\right] s(t) dt \qquad (6)$$

Equation 6 has the advantage of time and frequency diversities unlike the FFT transform that has only frequency diversity advantage. In fact, it has been explored that orthogonal wavelet-based OFDM is more robust to ICI and ISI problems than the FFT-based OFDM [19-21]. Meanwhile, the CP pre-appended to the OFDM symbol when using the FFT is omitted in the wavelet-based OFDM. This provides additional 25% spectral efficiency.

III. System Model

In the following, the system architecture is discussed for the forms of OFDM kernels just discussed. Since the fading for each transmission branch in a multi-antenna system between a pair of transmit and receive antennas are usually independent, the probability that the information is detected correctly is increased [11]. Thus, the probability that the transmit signal will be decoded correctly increases with the diversity order. On that note, let there be a MIMO-OFDM system with N_T antennas and N_R receive antennas defined for N-subcarrier OFDM existing for each transmit antenna. Let there be also n^{th} OFDM subcarrier symbol, $s_k^p(n)$, transmitted over p^{th} transmit antenna at k^{th} OFDM symbol duration. It can be identified that the OFDM symbol of this characteristics– $s_k^p(n)$– will exploit frequency, space and time diversity gains by the notations following the OFDM symbol, $s(.)$.

A. General System Model

For the FFT-based OFDM, IFFT is applied and the CP is pre-appended to each of the symbols. In the case of wavelet-based OFDM, the wavelet transform is applied to the codeword and then transformed to frequency domain – to fully exploit the frequency diversity gain. The channel is entirely doubly selective (except for times at which the Doppler frequency is explicitly null), although the OFDM technology transforms the frequency-selective channel into a frequency flat fading channel.

In the receiver (after removing the CP for the FFT-OFDM case), the received symbol is OFDM-detransformed using FFT or forward wavelet transform as the case may be. So for each transmit symbol from one transmit antenna,

$$R_k^q(n) = \sum_{p=1}^{N_T} H_{p,q}(n) S_k^p(n) + Z_k^q(n), \forall n = 0, 1, \Lambda, N \qquad (7)$$

where $R_k^q(n)$ is the nth received OFDM symbol with $H_{p,q}(n)$ as the frequency domain channel gain corresponding

to p^{th} transmit antenna and q^{th} receive antenna respective for every subcarrier. The channel gain corresponds to the individual resolvable paths traversed by the OFDM symbols with impulse response vector:

$$\boldsymbol{h_{p,q}} = [h_{p,q}(0), h_{p,q}(1), h_{p,q}(2), \Lambda, h_{p,q}(L-1)] \in C^{L \times 1} \quad (8a)$$

where $C^{L \times 1}$ is a complex matrix of $L \times 1$ dimension. The channel gains then follow as:

$$H_{p,q}(n) = \sum_{l=0}^{L-1} h_{p,q}(l) \cdot e^{-j2\pi f \tau_l} \quad (8b)$$

where $e^{-j2\pi f \tau_l}$ is the DFT factor for transforming from time to frequency domain, $Z_k^q(n)$ in Equation 7 is the additive white Gaussian noise (AWGN) while $S_k^p(n)$ is the space-time-frequency (STF) codewords of the N_T transmit antenna, N_R receive antenna of N_Δ OFDM symbol interval. By imaging the STF in three-dimension (3D), STF will be seen as a point on that plane [15]. Like in [22, 23], the diversity gain will increase by the number of subcarriers used such as $N_T N_\Delta N_R$. For each sub-channel, the STF codeword is constructed as follows:

$$S(n) = \begin{bmatrix} S_1^1(n) & \Lambda & S_1^{N_T}(n) \\ M & O & M \\ S_{N_\Delta}^1(n) & \Lambda & S_{N_\Delta}^{N_T}(n) \end{bmatrix} \in C^{N_\Delta \times N_T} \quad (9)$$

In Equation 9, $S(n)$ can be taken as orthogonal space-time block code already discussed in [24, 25]. In terms of STBC, Equation 7 can then be expressed as [26];

$$R(n) = \sqrt{\frac{\rho}{N_T}} H(n)S(n) + Z(n)$$

where ρ is the SNR respective to each transmission branch (antenna), $Z(.)$ is additive noise with circular symmetry and zero mean. To exploit the STBC basic criterion, Equation 9 must be designed according to the design criteria of [25] and given as:

$$s = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \quad (10)$$

Traditionally, full diversity of an orthogonal STBC system is derived from the pairwise error probability between two different codeword matrices (usually transmitted and received), say $\boldsymbol{S}$ and $\boldsymbol{S'}$ bounded as [26]:

$$P(\boldsymbol{S} \rightarrow \boldsymbol{S'}) \leq \binom{2r-1}{r} \left(\prod_{i=0}^{r} \gamma_i \right)^{-1} \left(\frac{\rho}{N_T} \right)^{-r} \quad (11)$$

Equation 11 can also be used to discuss the BER statistics of space-frequency block coding (SFBC); In fact, the BER statistic of STBC and SFBC are similar [27] where the upper bound, r, is the *rank* of: $(\boldsymbol{S-S'})\boldsymbol{R}(\boldsymbol{S-S'})^H$ where $\boldsymbol{R} = \mathrm{E}\{H H^H\}$

is the correlation matrix of the channel matrix and $\gamma_1, \gamma_2, \ldots, \gamma_r$ are nonzero eigenvalues of $(\boldsymbol{S-S'})\boldsymbol{R}(\boldsymbol{S-S'})^H$. The superscript in $(.)^H$ is a Hermitian transpose operator and H represents the channel matrix. Signals $\boldsymbol{S}$ and $\boldsymbol{S'}$ are transmitted and received signals respectively. Recently, the BER statistic of the STFBC has been explored in [15, 28].

B. Example of an orthogonal STBC – the Alamouti Code

The traditional Alamouti STBC is followed in which the system will be assumed to be constant over two symbol periods. s_1 and s_2 are transmitted in the first symbol period, and their conjugates (s_1^* and $-s_2^*$) are transmitted in the second symbol period. In Figure 2, this is replaced with the FFT. In Figure 2, s_1 will be transmitted using antenna T1 and s_2 using antenna T2 in the first time period. In the second time period, the negative conjugate of s_2, i.e. ($-s_2^*$), and the conjugate of s_1, i.e. s_1^*, will be transmitted over antennas T1 and T2 respectively.
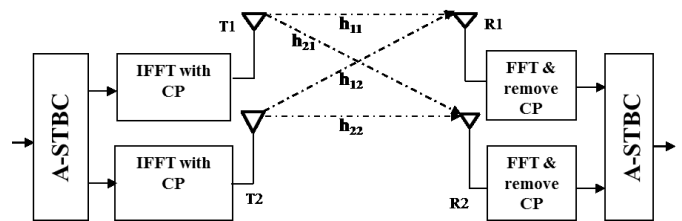

Fig. 2. Simple 2x2 MIMO-OFDM Modulation Architecture

Let $s(n)$ be the discrete equivalent of the original OFDM information $s(t)$, then s_1 and s_2 can be obtained as [29, 30]:

$$s_1 = \frac{1}{\sqrt{2}} s(n) \quad (12a)$$

$$s_2 = \frac{1}{\sqrt{2}} s(n) \quad (12b)$$

The code structure formed from Equation 12 following Equation 9 and 10 is an STF codeword. In that case, S, S_1 and S_2 are frequency domain contents of s, s_1 and s_2 respectively. Equation 12 will convolve with the doubly selective frequency domain channel gains of h_1 and h_2, as of the channel transfer function in Equation 8b such as:

$$R_1 = H \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} + Z_1 \quad (13a)$$

and,

$$R_2 = H \begin{bmatrix} -S_2^* \\ S_1^* \end{bmatrix} + Z_2 \quad (13b)$$

where $H = [H_1 \quad H_2] = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$ \quad (14)

By Equation 14, there are up to 2 number of receive antennas. The received signals estimates of the transmitted symbol will then be computed. These estimates are obtained as:

$$D_1 = H_1^H R_1 + R_2^H H_2 \qquad (15a)$$

and,

$$D_2 = H_2^H R_1 - R_2^H H_1 \qquad (15b)$$

where $(\cdot)^H$ denotes a Hermitian operator. The foregoing description limits $N_T = 2$ and up to $N_R = 2$.

C. Doppler Effect in OFDM Systems - Single Antenna Case

Consider a traditional frequency–selective channel as (in time domain) [31];

$$h(t,\tau) = \sum_{l=0}^{L-1} \alpha(l) e^{j\phi_l} \delta(t - \tau_l) \qquad (16)$$

where $\alpha(l)$ is the lth amplitude of the lth path traversed by the OFDM symbol, $\phi_l(t) = 2\pi \{(f_c + f_{d,l})\tau_l - f_{d,l}t\}$ is the phase, f_c is the carrier frequency, τ is the path delay and $\delta(.)$ is the dirac delta function. The received OFDM signal in the receiver will be;

$$r(t,\tau) = \frac{1}{\sqrt{LT}} \sum_{l=0}^{L-1} \alpha(l) e^{j\phi_l} s(t - \tau_l) \qquad (17)$$

So, each of the received signals is delayed by τ_l and scaled by $\alpha(l) e^{j\phi_l}$. If frequency domain content of Equation 16 is considered as well as the doubly-selective characteristics of the channel (i.e. t and f):

$$H(t,f) = \sum_{l=0}^{L-1} h(t,\tau) \, e^{-j(2\pi l)/N} \qquad (18)$$

Notice that $h(t,\tau_l) \in C^{L \times 1}$, where $C^{L \times 1}$ is a complex matrix of $L \times 1$ dimension. The term ϕ_n influences the phase rotation of received OFDM symbols and it involves $\phi_l = \phi_n + \phi_{off}$, where f_d is the maximum Doppler frequency and ϕ_{off} is the carrier frequency offset. In this work, so set $\phi_{off} = 0$. The transmit signal convolves with Equation 18 such as;

$$R(t,f) = \frac{1}{\sqrt{LT}} \sum_{l=0}^{L-1} H(t,f) S(f) \qquad (19)$$

where $S(f)$ is the frequency content of $s(t - \tau_l)$. The Doppler frequency shifts the signal from the carrier frequency which in turn affects the amplitude of the received symbol. For signal compensation, we proceed as follows;

$$Y(t,f) = \frac{H(t,f)^H R(t,f)}{\|H(t,f)\|^2} \qquad (20)$$

where $H(t, f)^H$ is the Hermitian of the matrix $H(t, f)^H$. Equation 21 is then transformed into the time domain. If at a time that $|H(t, f)| = 0$, then Equation 21 is modified as:

$$Y(t,f) = \frac{H(t,f)^H R(t,f)}{\|H(t,f)\|^2 + \varepsilon} \qquad (21)$$

This is equivalent to:

$$Y(t,f) = \frac{H(t,f)^H \cdot H(t,f) S(t,f)}{\|H(t,f)\|^2 + \varepsilon} + \frac{H(t,f)^H \cdot Z(t,f)}{\|H(t,f)\|^2 + \varepsilon}, \; \forall 0 \le \varepsilon \le 1 \qquad (22)$$

where $(.)^H$ is the Hemitian operator, $H(t,f)^H \cdot H(t,f)$ is unitary. The term ε is an error correction factor to reduce the magnification of the noise parameter due to equalization.

D. Doppler Effect in OFDM Systems for Multi-Antenna Case

In earlier studies of the ST codes for MIMO systems, the channel model is usually treated as frequency flat-fading channel. However, each of the transmission branches is independent. This necessitates that the likelihood of decoding the signals correctly increases. MIMO-OFDM systems for realistic broadband channel is non-frequency flat, instead frequency-selective which the OFDM converts to flat-fading channel to eliminate ISI. Meanwhile, for varying mobile speeds the channel also varies in time contributing time-selectivity so that the broadband channel be doubly (time-frequency) selective. This is the case for each transmission channel branch in this study discussed in Section III-*A*. Thus, for the STF block codes used in this study, each of the transmission branches is necessarily doubly selective so that the Doppler frequency can be accounted for at varying mobile speeds.

IV.   SIMULATION RESULTS AND DISCUSSION

The simulation was carried out, first for the single antenna transmission and then the MIMO antennas systems. The operating frequency deployed is the new operating frequency 800MHz and 2.6GHz for LTE-advanced. The rest higher frequencies (900MHz and 1800MHz for GSM) were not investigated. In general, the QPSK modulation scheme was used over OFDM system whose channel delay spread is in the order of the outdoor environment at a sampling frequency of 20KHz.

The mobile speeds are typical for standard road (and railway) travels – 120Km/hr, 150 KM/hr, 200Km/hr, 240Km/hr and 280Km/hr are investigated. The number of OFDM subcarriers used is 64 with 25% cyclic prefix for the case of FFT-OFDM. This is not applicable to wavelet-OFDM by the considerations described in this work, thus offering the wavelet-OFDM further 25% spectrum efficiency at the expense of the FFT-OFDM.

A. SISO OFDM System

The SISO-OFDM systems considered are for the FFT-based and wavelet-based OFDM systems. Each has been simulated over the same design parameters except for the FFT-OFDM using cyclic prefix of 25% only.
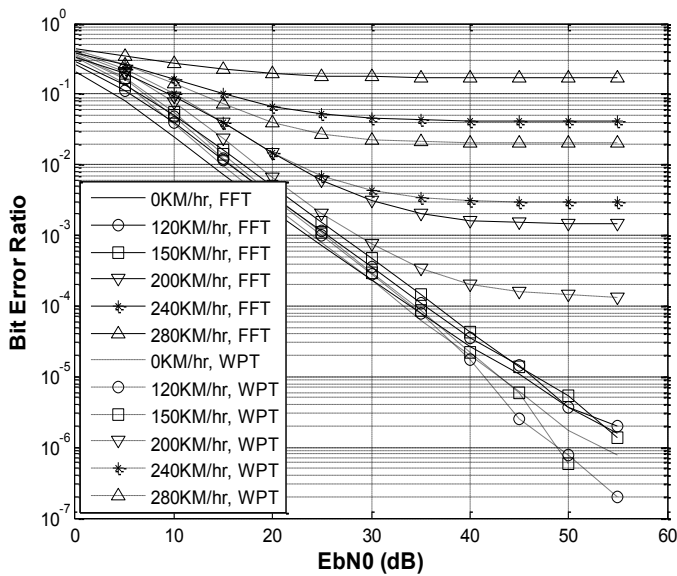
Fig. 3. Comparison of FFT-OFDM and wavelet-OFDM at 800MHz for SISO Systems

Recall that the FFT-OFDM is highly robust over frequency selective channel [32]; $f_d = 0$ in that case. From Figures 3 and 4, it can be seen that the FFT-OFDM contended favourably with the wavelet-OFDM when the channel is dominantly frequency-selective. However, for other speeds shown in the results, wavelet-OFDM well outperformed the FFT-OFDM.
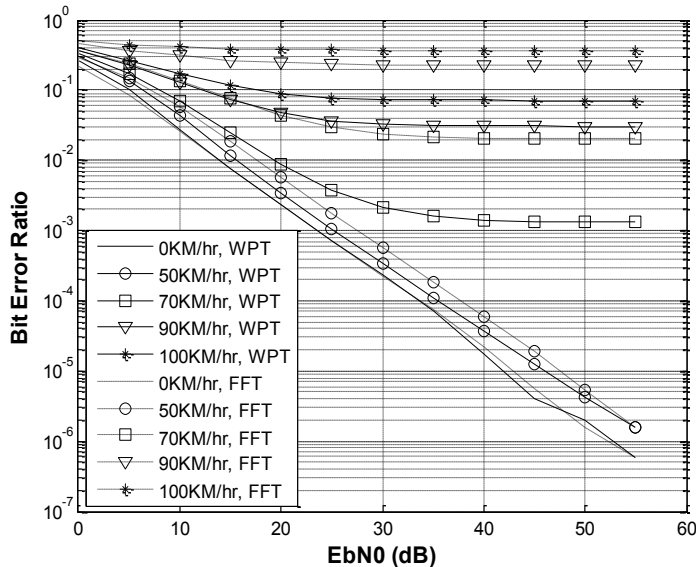

Fig. 4. Comparison of FFT-OFDM and wavelet-OFDM at 2.6GHz for SISO Systems

Results in Figure 4 show the consistence of wavelet-OFDM robustness over doubly selective transmission. Meanwhile, the results reveal that the 2.6GHz has poorer performance than the 800Hz operating carrier frequency since the fading bandwidth of the channel increases with the operating carrier frequency.

B. MIMO-OFDM

In MIMO-OFDM case, Figure 5 depicts the performance of FFT-OFDM and wavelet-OFDM for a MISO System for different mobile speeds.
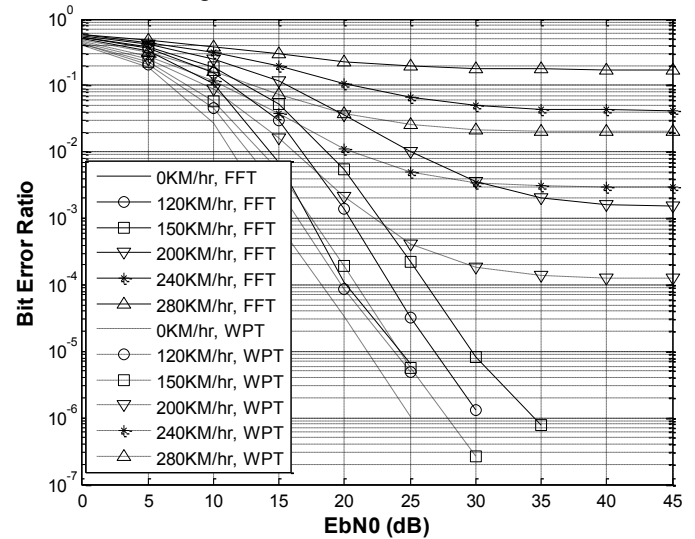

Fig. 5. Comparison of a 2x1 FFT-OFDM and wavelet-OFDM Systems at 800MHz

It is obvious that the wavelet-OFDM outperformed the FFT-OFDM for all speeds. In the next result (Figure 6), it is shown that the result in Figure 5 is improved for a 2x2 MIMO system. We conjecture that this result in Figures 5 and 6 may be consistent for 2x1, 2x2 or even higher order MIMO configurations above 2.6GHz operating frequency, with wavelet-OFDM dominating FFT-OFDM in performance.

In general, the degree at which the OFDM signal shifts from the carrier (or equivalently centre frequency in the baseband) frequency, f_c, by Doppler shift depends on the property of the signal volunteered by the baseband transform. The Doppler Effect leads to the loss in orthogonality of the sub-channels of the OFDM system. Wavelet transforms the signal to possess time and frequency diversities whereas the FFT provides frequency-selectivity (diversity) only. The robustness of the signal against the Doppler shift is then dependent on characterizing signal property nominated by the baseband transform used in the signal multiplexing.

V. CONCLUSION

Future generation wireless communication design of radio air-interface such as the OFDM was presented for two different design kernels − fast Fourier transform and wavelet packet transform. Both OFDM systems were investigated for different mobile speeds which account for varying Doppler frequencies effect in high speed wireless communications typical of real-life scenarios. OFDM converts frequency-selective channel into flat fading channel thus very robust in frequency-selective transmission. However, the FFT-OFDM scheme was observed to be sub-optimal compared to the wavelet transform for OFDM design for high speed mobiles. Results reveal that the wavelet-OFDM has very robust ability in repelling the inter-carrier interference volunteered by fast fading channels due to Doppler Effect than the FFT-OFDM.

Thus, the wavelet transform can be a good candidate for the seamless broadband network radio air-interface in future wireless communications.
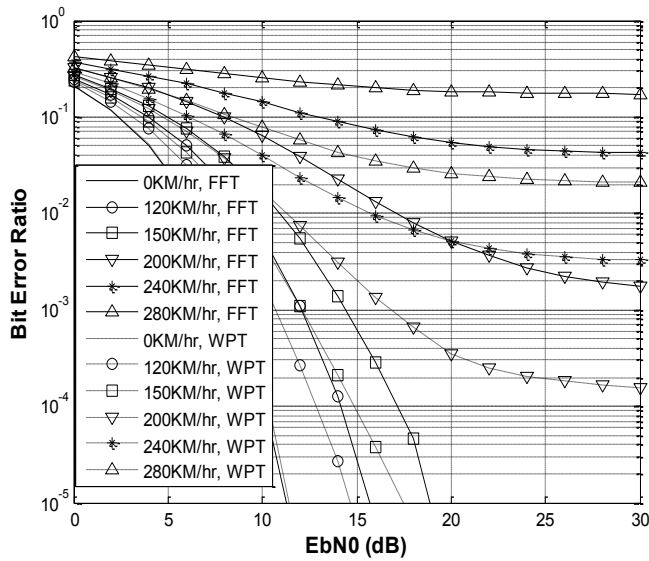

Fig. 6. Comparison of a 2x2 FFT-OFDM and wavelet-OFDM Systems at 800MHz

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