On The ICI Mitigation Techniques in High Mobility MIMO-OFDM Systems with Parallel ICI Cancellation under Various Normalized Doppler Spreads

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Abstract

The signals of LF and VLF are rapidly alternated by the earth's surface; and there are various propagation models currently used by the wireless industry for signal transmission within the frequency range 150-1800 MHz. Hata-Okumura two rays model are one of them. This paper addresses the problem of Inter Carrier Interference (ICI) arising from the Doppler shift caused by the high mobility in areas covered by OFDM based systems via High Altitude Platforms (HAPs). The proposed scheme presented in this paper is for Doppler assisted channel estimation with the parallel interference cancellation with decision statistical combining scheme (PIC-DSC) for high mobility MIMO-OFDM systems to improve the ICI cancellation which is essential in enhancing the BER performance which induces a large frequency offset error. The simulation results shows that the outperforms convergence characteristic of channel estimation with the PIC-DSC interference cancellation scheme - under various normalized Doppler spreads (e.g., normalized Doppler spread of 0.1 and 0.025) at SNR 20dB and 30dB - has better symbol error rate (SER). The algorithm is efficiently mitigates ICI under Quadrature Phase Shift Keying (QPSK) modulation showing Bit Error Rate (BER) performance analysis and compared with other existing schemes.

Keywords*:* Multiple-input multiple-output (MIMO), Inter-Carrier Interference (ICI), High mobility, Doppler Spread, Carrier Frequency Offset (CFO), Channel State Information (CSI).

1-Introduction

One of the most common models for signal prediction in large urban macro-cells is Okumura's model. This model is applicable over distances of 1-100 Km and frequency ranges of 150-1500 MHz. The Okumura model for urban areas is a radio propagation model that was built using the data collected in the city of Tokyo, Japan. The model is ideal for using in cities with many urban structures but not many tall blocking structures. The model served as a base for the Hata model. It was built into three modes (urban, suburban and rural areas), the model for urban areas was built first and used as the base for others, it is more frequently used for estimating cell radius usually 50-60% path loss is accepted for urban areas. On the other hand; it is 70-75% for rural areas as in [1]. In this phase; the analysis will be extended to the case of mobile users (Doppler shift) co-existing with randomly distributed but stationary users in co-channel cells. A specific system model will be put forward in order to evaluate system dependent parameters, e.g. Bit Error Rate (BER) - as a function of the Signal to Interference plus Noise Ratio (SINR) and the normalized Doppler shift. The model will also rely on semi-analytical techniques as well as some theoretical aspect as possible. The research methodology that characterizes this phase is the iterative convergence towards the results by extensive simulations as in [2]. Reference [3] is recommended to start firstly to this phase by a brief review and re-implementation of the results we have previously; for the average link capacity in a multi cell MIMO system covered by HAP. As the results confirms that the use of MIMO system will greatly increase the achievable rate (capacity) on Rayleigh fading channels with certain degree of correlation and shows that multi cell MIMO systems covered by HAP outperforms conventional terrestial in terms of the per user link capacity as the performance metric of interest.

2-Problem Statement

OFDM by itself has the advantage of turning the frequency response of a frequency selective channel into a flat nonselective fading channel. However, in fading channels with very high mobility, the time variation of the channel envelope over an MIMO-OFDM symbol period results in a loss of the sub carrier orthogonality which leads to inter-channel interference (ICI) due to power leakage among MIMO-OFDM subcarriers.

2-1 Synchronization Error

It can be assumed that most of the wireless receivers cannot make perfect frequency synchronization, in fact, practical oscillators for synchronization are usually unstable, which introduce frequency offset (FO). Although this small offset is negligible in traditional communication system; but for OFDM system it is a severe problem. In most situations, the oscillator frequency offset varies from 20parts per million (ppm) to 100ppm. Provided an OFDM system operates at 5GHz, the maximum offset would be 100kHz to 500kHz (20-100ppm.). However, the subcarriers frequency spacing is only 312.5 kHz. Hence; the frequency offset could not be ignored, but it can be normalized by the reciprocal of symbol duration. For example, if a system has a bandwidth of 10MHz, and the number of subcarriers is 128, then the subcarrier frequency spacing would be 78kHz. If the normalized frequency offset is larger than 1, only the decimal part needs to be considered as in [4].

3. System Model

3.1 Signal and Channel Models

The block diagram of a MIMO-OFDM system transmitter is shown in Fig. 1(a) - considering MIMO-OFDM system with MT transmit and MR receive antennas. At the transmitter side, a serial bit stream is mapped to a symbol stream by a modulator, then; this serial symbol stream is converted into parallel sub-streams. Next pilot symbols for the channel estimation are inserted into these parallel sub-streams in the frequency domain prior to the OFDM modulation. The OFDM modulation is then implemented by performing inverse discrete Fourier transform (DFT), each transmit antenna sends independent OFDM symbols.

Let Xp(k) denote the information symbol sent by transmit antenna p at subcarrier k, the OFDM symbols transmitted by MT transmit antennas can then be presented as:

$$X = [X1, \ldots, Xp, \ldots, XMT\ ]\ T \quad (1)$$

Where, Xp = [Xp(0), . . . , Xp(N − 1)] T is the OFDM symbol transmitted from the p^{th} transmit antenna, and N is the number of subcarriers for one OFDM symbol. After performing inverse DFT (IDFT) on each transmit antenna, the time-domain modulated signal on the pth transmit antenna can be expressed as

$$xp = FHXp = [xp(0), \ldots, xp(N-1)]\ T \quad (2)$$

Where, F is the N × N DFT matrix with its element at row n and column k, which is defined as wn, k= e(−j2πnk/N) for n, k = 0, . . . , N−1. To avoid Inter Symbol Interference (ISI) due to a multipath delay spread, a cyclic prefix of length equal or greater than the expected maximum time delay of the channel is inserted in each OFDM symbol prior to transmission. This prefix serves as Guard Interval (GI) between OFDM symbols. Finally, the symbol streams are converted from a parallel to a serial form and allocated to corresponding transmitters for transmission. The block diagram of a MIMO-OFDM system receiver is shown in Fig. 1(b) as in [5]-[7].

At the receiver side, once the GI is removed, the received signal at the *q*th receive antenna and time *n* can be represented as

$$rq(n) = \sum_{p=1}^{MT} (hp,q(l,n) \otimes xp(m))\omega q(n) \quad (3)$$

$$= \sum_{p=1}^{MT} \sum_{l=0}^{L-1} (hp,q(l,n)xp(n-l) + \omega q(n) \quad (4)$$

Where $\otimes$ is the cyclic convolution, *wq*(*n*) is the additive white Gaussian noise (AWGN), and *hp*,*q*(*l*, *n*) is the impulse response of the *l*th channel tap between the *p*th transmit antenna and the q^{th} receive antenna at time *n*. From the model introduced about that; the expression of the received signal must generally include a possible phase error. However, the ICI effects may or may not be mitigated effectively without the original phase error information. This is done either by assuming a perfect synchronization of the receiver's local oscillator with the incoming RF carrier or the ICI mitigation technique may not require information about the phase error at all as in [8].

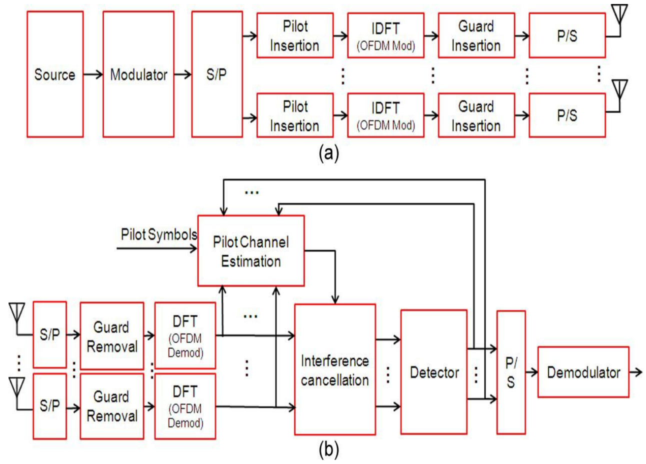

Fig. 1 Block diagram of the OFDM system (a) Transmitter (b) Receiver

4. ICI Cancellation Technique

ICI cancellation techniques are essential in improving the Bit Error Rate (BER) performance of OFDM systems in an environment which induces a large frequency offset error. A lot of ICI mitigation methods have been extensively investigated to combat the ICI, including the following:

1. Channel Estimation with Frequency-Domain Equalization (CE-FDE).
2. Time-domain windowing filters.
3. Self-cancellation schemes.
4. Frequency offset estimation and tracking techniques.

4.1 Channel Estimation with Frequency Domain Equalization

The advantages of OFDM of viewing the channel as a single tap channel, thus; a simple one tap equalizer is needed to estimate the channel and recover the data. The techniques for equalization in high mobility channels are generally classified as linear equalization: a zero-forcing (ZF) equalizer or the Minimum Mean Squared Error (MMSE) equalizer in frequency domain was proposed by ignoring the ICI terms which have insignificant influence on the desired signal. While nonlinear equalization is classified by: Decision Feedback Equalizers (DFE), after MMSE; the complexity and performance trade-off become better. Its complexity grows linearly with the number of transmit antennas and transmission rate and the effect of the AWGN is eliminated as in [9],[10]. The following scheme is presenting the parallel interference cancellation with decision statistical combining (PIC-DSC):

In the first stage (soft decision), the received signal at each time slot is given by:

$$r_t = H\, x_t + n_t \qquad (5)$$

Where, r_t is received signals across the n_r receive antennas, x_t is the transmitted signals and n_t is the AWGN noise signals from the receive antennas,

$$y_t = w^H_i\ r \qquad (6)$$

Where, w is an $n_r \times n_t$ matrix of linear combination coefficients given by:

$$w^H = [\, H^H H + \sigma^2 I_{nt}\,]^{-1} H^H \qquad (7)$$

Where, σ^2 is the noise variance.

In the second stage (hard decision), min E {(x − w H r) 2 }

$$x\Lambda^t_i = q\,(y^t_i) \qquad (8)$$

In the algorithm - with interference suppression only - the detector calculates the hard decisions estimates by using the above equation for all transmit antennas. In interference suppression and interference cancellation, a soft decision is given by:

$$y^t_i = w^H_i\ r \qquad (9)$$

Where, i is the transmitting antenna number and hard decisions:

$$x\Lambda_i^t = q(y_i^t) \quad (10)$$

$$r^{i-1} = r^i - x\Lambda_i^t \; h_i \quad (11)$$

Where, hi is the ith column in the channel matrix H

One of the disadvantages of the MMSE scheme with successive interference cancellation is that the first desired detected signal to be processed sees all the interference from the remaining ($n_T - 1$) signals, whereas each antenna signal to be processed later sees less and less interference as the cancellation progresses as shown in Fig. 2, the ZF versus MMSE equalizers for QPSK. This problem can be alleviated either by ordering the layers to be processed in the decreasing signal power or by assigning power to the transmitted signals according to the processing order as in [11]-[13].

4.2 Comparison

Nonlinear equalizers generally outperform linear approaches; however, linear equalizers still preserve their importance mainly because they are less complex. But, since the number of subcarriers is usually very large, may reach about 8,096 in high speed wideband wireless standards, even linear equalizers demand very high computational load.

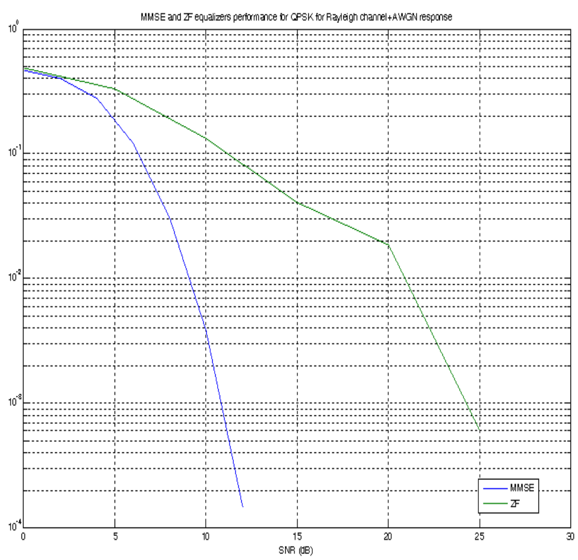

Fig. 2 ZF vs. MMSE Equalizers in MIMO multiplexing systems for QPSK modulation.

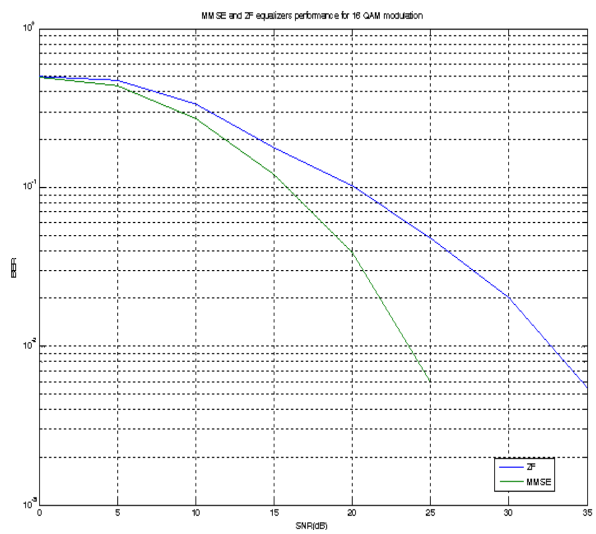

Fig. 3 ZF vs. MMSE Equalizers in MIMO multiplexing systems for 16QAM modulation.

Fig.3 shows the ZF versus MMSE for 16QAM. The main factor that affects the rate of fading is the mobility of the receiver relative to transmitter - as the receiver moves with some velocity relative to the transmitter and the phase shifts of the received signal changes (Doppler shift). The specific structure of the Doppler induced ICI matrix in OFDM systems operating over highly mobile channels is a distinctive feature of each proposed receiver. On the other hand, the recent work on the separate equalization and estimation for OFDM systems in a highly mobile environment can be summarized as in the following section.

For a rapidly time varying Doppler channel, the time domain channel estimation method proposed in is a potential candidate for the channel estimator in order to mitigate the ICI. This technique estimates the fading channel by exploiting the time-varying nature of the channel as a provider of time diversity and reduces the computational complexity using the singular-value decomposition (SVD) method. However, the linear MMSE successive detection with optimal ordering proposed in along with channel estimation demand very high computation, since the number of subcarriers is usually very large; thus it may not be feasible in practical systems as in [14],[15].

4.3 Complexity Reduction in complex exponential/Equalization

Most of the complexity reduction techniques depend on a finite power series expansion for the time varying frequency response is used and channel acquisition and ICI removal are accomplished in the frequency domain. This is instead of assuming that the channel is banded as in low mobility environments complex exponentials as in [14].

4.3.1 Time Domain Windowing Filters

Time windowing methods have the advantages that they reduce the required SNR to achieve the BER than that do not use time domain windowing. Fig. 4, shows the BER of an OFDM system vs. SNR (dB) - QPSK modulation. They need redundant information, performance of the windowing methods degrade significantly with the increase of frequency offset. The BER performance levels off with increasing the SNR and is not a monotonically decreasing function of the SNR.

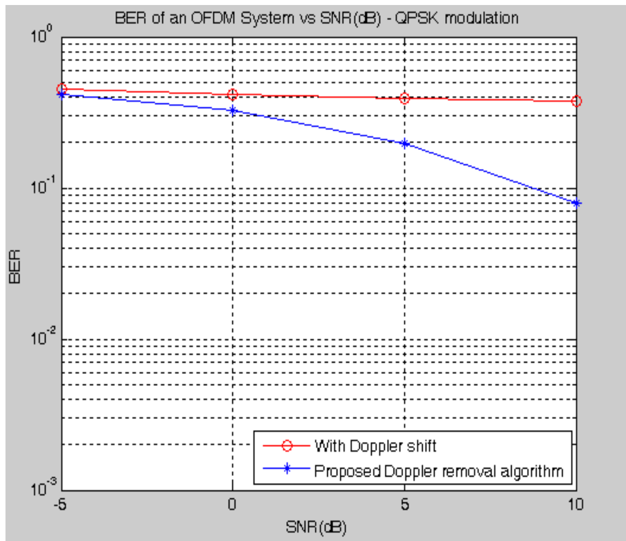

Fig. 4 BER of an OFDM system vs. SNR (dB) - QPSK

- ***Self Cancellation Schemes***

Among the methods, the ICI self cancellation method is a simple way to suppress ICI that uses redundant modulation. Several self-cancellation methods have been exploited, including data conversion, data conjugate and symmetric data-conversion/conjugate methods. The advantage is gain with high accuracy, but the performances of the self-cancellation methods degrade significantly with the increase of frequency offset, and the data low efficiency which increase system high computational complexity.

- ***Frequency Offset Tracking by Kalman Filter (KF)***

Several of algorithms have been developed for Carrier Frequency Offset (CFO) estimation in OFDM. KF algorithms belong to the frequency offset estimation and compensation methods. Fig. 5, shows the FO tracking by KF, in this method; the received signal is divided into real and imaginary parts.

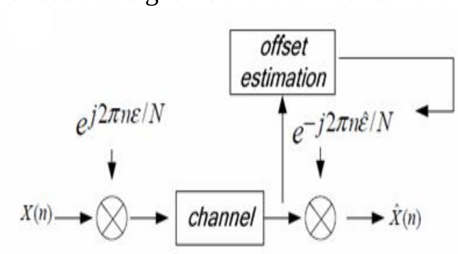

Fig. 5 Frequency Offset Tracking by Kalman Filter (KF).

With some relationship between the real and imaginary parts, the KF is used to estimate the frequency offset regardless of the estimate of original phase of carrier. KF is an adaptive one and hence; the Doppler frequency drift information can be updated at each step to get a more accurate result as in [16].

- Extended Kalman Filter (EKF)

The EKF which is based on Taylor series linear approximation of the received signal model. The main disadvantage is that the Doppler Effect with noise is actually a non-linear Gaussian process, so the approximation is not very accurate, in addition to calculating the Jacobean matrices, may increase the computation complexity such that the system runs out of real time applications. This lead to proposing what is called Unscented Kalman filter (UKF), which is based on is unscented transformation of the joint distribution and has the advantages that; UKF performances better at capturing the higher order moments caused by the non-linear transform and the computation of Jacobean matrices is not needed, so the estimation procedure is in general easier and less subject to errors. But, on the other hand it the estimated value by this algorithm is not accurate when Doppler shift is larger [17]-[19].

From what was presented, the performances of the time domain windowing methods and the self cancellation methods is degraded significantly with the increase of frequency offset. Also, KF algorithms belong to the frequency offset estimation and compensation methods, but its implementation is more complex than self cancellation methods. From Fig. 6, we can see that the proposed scheme outperforms convergence characteristic of channel estimation with the PIC-DSC interference cancellation scheme - under various normalized Doppler spreads (0.1 and 0.025) at SNR 20dB and 30dB - has better symbol error rate (SER).

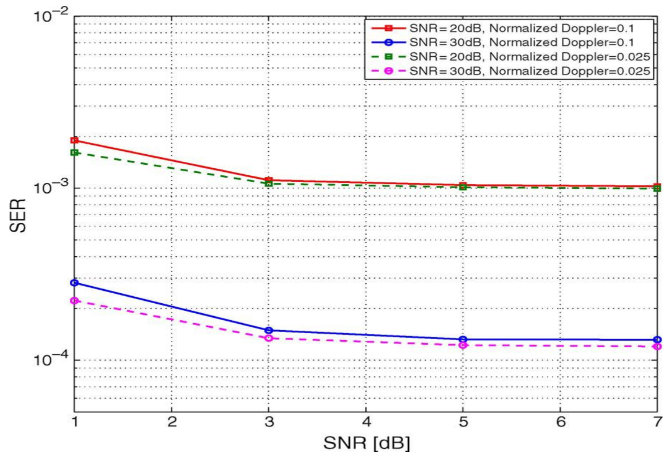

Fig. 6 Convergence characteristic of the proposed channel estimation with the PIC-DSC interference cancellation scheme under various normalized Doppler spreads.

5. Beam Forming Techniques

Another category to avoid complicated channel estimation and equalization is by some pre-processing method at the transmitter or receiver - such as frequency domain pre-coding. MIMO-OFDM symbol detection requires channel state information (CSI) estimation at the transmitter. The reliability of symbol detection depends on the accuracy of the channel estimation at the receiver. To accurately estimate the wireless channel, a number of subcarriers in an OFDM symbol are used as pilots, the remaining subcarriers are then either employed to transmit data symbols or set as unused carrier. In Water-Filling algorithm and SVD the case that the transmitter and receiver know the CSI matrix H, the capacity can be further enhanced by using a type of beam forming technique in which we assign unequal powers among the transmitter ports. The optimal power distribution method that can be used is known as the water filling algorithm. In such algorithm, the MIMO transmitter array is assumed to virtually divide the channel into independent decoupled sub-channels and beam forming of the radiated transmitted signal is performed to send information among these virtually decoupled sub-channels, in such a way that the best Eigen modes of the propagation channel, that is, the sub-channels with highest gain are selected as in [20]-[22]. Thus; water filling is an optimal method of power distribution among spatial MIMO sub-channels created using beamforming techniques, in which weaker channels are - in general - not used. In linear algebra, the SVD is a factorization of a real or complex matrix, with many useful applications in signal processing and statistics. Formally, the SVD of an m×n real or complex matrix M is a factorization of the form:

$$M = U\Sigma V^{*}, \tag{12}$$

Where U is an m×m real or complex, Σ is an m×n rectangular diagonal matrix with non-negative real numbers on the diagonal, and V* (the conjugate transpose of V) is an n×n real or complex unitary matrix. The diagonal entries Σi,i of Σ are known as the singular values of M. The m columns of U and the n columns of V are called the left singular vectors and right singular vectors of M, respectively. The singular value decomposition and the Eigen decomposition are closely related. Namely: The left singular vectors of M are eigenvectors of MM^*.

The right singular vectors of M are eigenvectors of M^*M.
The non-zero singular values of M (found on the diagonal entries of Σ) are the square roots of the non-zero eigen values of both M^*M and MM^*.

Applications which employ the SVD include computing the pseudo inverse, least squares fitting of data, matrix approximation, and determining the rank, range and null space of a matrix as in. If we assume the SVD of the CSI matrix H is given by the following equation:

$$\mathbf{H} = \mathbf{U\Lambda V^H} \qquad (13)$$

With $\mathbf{U}$ and $\mathbf{V}$ are the left and right singular vectors respectively. $(.)^H$ is the Hermitian operator and $\mathbf{\Lambda}$ is a diagonal matrix whose elements are the singular values λ_i of the CSI matrix H. These singular values are given by:

$$\Lambda = \mathbf{U^H H V} \qquad (14)$$

Where, Λ : is the uppercase notation of λ

The Hermitian operator $(.)^H$ is just the conjugate of the transpose of a complex matrix, that is, $(.)^H = \left((.)^* \right)^T$

The Power Distribution Function (PDF) of the matrix and elements (landas) as in [16], the average allocation and water – filling allocation depends on rank of the channel matrix H and by applying SVD in the statistical behavior of MIMO channels. The following two figures, (Fig. 7 and Fig. 8) are showing the PDF of elements in matrix landa in SVD decomposition of matrix H of nt x nr and the capacity of a MIMO channel with nt x nr nr antenna varying from 1 to 8 respectively. Recently, spatial diversity has attracted a lot of attention due to its capability to mitigate fading in wireless channels. Some techniques show that beam forming can alleviate the time-variance [23],[24].

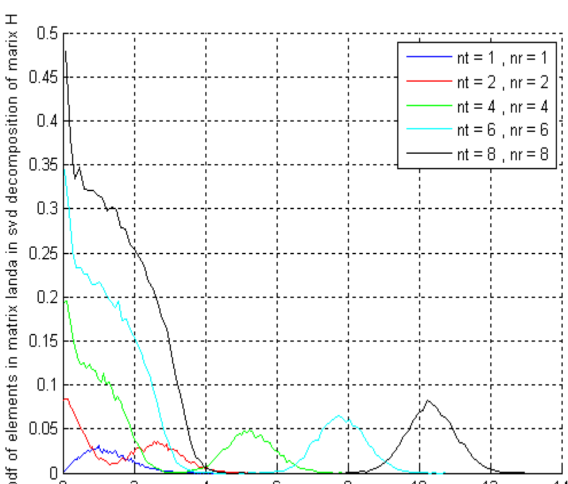

Fig. 7 Probability density function (PDF) distribution for MIMO channel with nt x nr receiver antenna varying from 1 to 8.

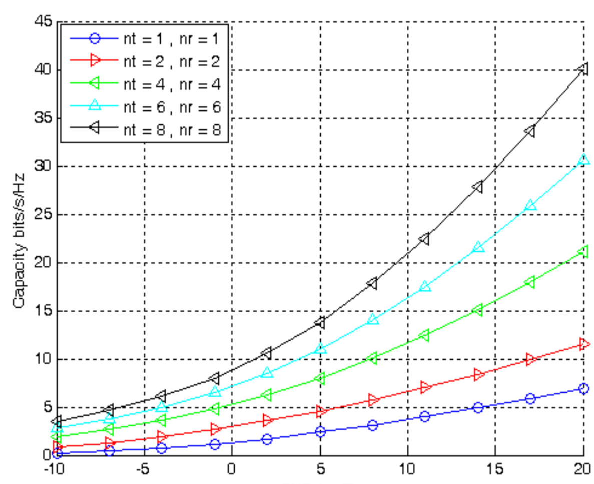

Fig 8 Capacity of a MIMO channel with nt x nr receive antenna varying from 1 to 8

If we use ideal directional antennas and sectorized antennas the ICI to be investigated. These works reveal that the ICI can be partially compensated by regarding the Doppler spread as an equivalent frequency shift in a certain sector.

In many cases, the space is divided usually into three sections according to the strength of ICI, which were processed respectively by dual antenna as in [24]. These schemes can narrow the Doppler spreading by ideal sectors and have low complexity increase in the baseband. The receiver can form ideal patterns in certain angles-of-arrival (AoA), it can focus on these AoA, and correct their Doppler shifts via a frequency shift and sum up again to compensate the Doppler spreading. The multiple directional paths after Doppler compensation are finally combined for extra performance gains. No remarkable advantages can be stated - since it is an alternative equivalent to the channel estimation and equalization techniques, the disadvantages is the perfect CSI is not always available at the transmitter site and needs a reverse link, hence low spectral utilization as in [25].

6. Conclusion

Throughout this paper, a highly scattered mobility environment is considered for the capacity of a MIMO channel with nt x nr is analyzed, the power in parallel channel (after decomposition) is distributed as water-filling algorithm of a PDF of the matrix lanada elements is depicted too. The algorithm is proposed to remove the Doppler shift arising from high mobility corresponding to a normalized Doppler shift of 0.2 or a speed of 120 km/hr. In this paper, the proposed scheme for Doppler assisted channel estimation with the parallel interference cancellation with decision statistical combining scheme (PIC-DSC) for high mobility MIMO-OFDM systems improve the ICI cancellation which is essential in enhancing the BER performance which induces a large frequency offset error. The wireless channel has been estimated by using the Doppler spread information; the simulation results show that the proposed scheme outperforms convergence characteristic of channel estimation with the PIC-DSC interference cancellation scheme - under various normalized Doppler spreads (0.1 and 0.025) at SNR 20dB and 30dB - has better symbol error rate (SER). Note that the normalized Doppler spread of 0.1 is equivalent to an LTE user moving at the speed of 324 km/h and operating in the 5GHz band with a sampling frequency of 7.68MHz.

7. Future Work

For future work, it would be interesting to study the performance of STBC-OFDM in fast fading channels, and to compare the advantages and disadvantages of both STBC-OFDM and other potential modulation techniques to be used for the future 4G wireless communication systems such as WiMax (IEEE 802.16m) and LTE advanced. Also, an STBC-OFDM system will suffer from two kinds of interference in time varying channels. One of them is the ICI caused by variation of the received subcarrier multipath channels within an OFDM symbol; it would be interest for research to study the effect of ICI and how it will significantly degrades the system performance under high mobility, and to focus on the computation complexity.

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