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Inter-carrier interference power of OFDM in a uniform scattering channel

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ABSTRACT

This letter derives the upper and lower bounds on inter-carrier interference (ICI) power P_{ICI} of OFDM in a uniform scattering channel. The bounds are computed as functions of $f_d T_s$ product of the maximum Doppler spread f_d and symbol duration T_s, ζ frequency tracking and ϵ mobile travelling direction. Insightful discussions on the characteristics of P_{ICI} are given. Future work is also outlined.

1. Introduction

Inter-carrier interference power (P_{ICI}) in OFDM wireless communication systems is undesirable and should be reduced to the minimum to improve transmission efficiency. It was shown in [1] that the theoretical expression of P_{ICI} is difficult to interpret. Motivated by this fact, the universal bound was derived in [1] which specifies the upper limit of P_{ICI} for any Doppler spectrum $P(f)$. From a different view point, Ng and Dubey investigated the effectiveness of directional and non-directional antennas in wireless OFDM systems to reduce P_{ICI} using different scattering distributions. The system comprises of a base station (BS) receiving and transmitting signals from and to a mobile user equipment (UE) with random scatterers between them. The scatterers form a scattering channel which is characterised by their distribution $p(\theta)$. The P_{ICI} as a function of the scattering channel between the BS and UE was also derived. In addition, to compensate for Doppler spread and the mobile travelling direction ϵ and frequency tracking ζ was employed.

OFDM and ICI have recently attracted attention from researchers world wide. A new algorithm for ICI reduction using ICI as a diversity source and Weiner filter was proposed in [2] from which the detection and computation times were improved. A two-stage hybrid channel estimation and ICI cancellation structure for OFDM systems were studied in [3] in which encouraging results were obtained. A channel estimation and ICI cancellation algorithm with low complexity were proposed in [4] based on a basis expansion model (BEM) in fast-varying time channels with satisfactory results. Most pulses reported in the literature can either reduce the out-of-band emission and ICI but not both. An optimal pulse to effectively reduce both the out-of-band emission and ICI was proposed in [5] with encouraging results. On this note, a new pulse shape was proposed in [6] with additional analyses on bit error rate (BER) of the corresponding OFDM system. Detailed comparisons with other pulses were also given. Inter symbol interference (ISI) and ICI reduction algorithms for cooperative space–frequency block-coded OFDM (SFBC-OFDM) networks employing amplify-and-forward (AF) and decode-and-forward (DF) schemes were shown in [7] in which new algorithms were practically tested and better results were obtained. ICI was shown not only to cause performance degradation but also phase noise in OFDM systems [8]. Seo et al. [9] proposed a novel ICI reduction algorithm for ubiquitous environments. Their findings showed that using the new algorithm, BER and spectral efficiency of OFDM systems can be improved. An extended H filter-based ICI estimator was proposed in [10] from which the BER of OFDM systems can be significantly improved under unknown-noise conditions. An effective algorithm to combat ICI was proposed in [11] by employing linear filters and null sub-carriers. The algorithm was shown to improve OFDM reliability and more robust against Doppler spread. A two-step estimator in estimating channel common phase errors in the first step and removing ICI in the second step using a power series expansion of the phase noise process for coded and uncoded OFDM systems was reported in [12] with satisfactory results. Two methods for ICI reduction were studied in [13]: (i) using an extended Kalman filter (EKF), and (ii) employing the sequential Monte Carlo (SMC) called sequential importance sampling (SIS). The two methods were thoroughly assessed for different values of frequency offsets and

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signal-to-noise ratios. A two-stage precoder/equalizer was proposed in [14] to effectively combat ICI from which it was found that an improve of about 10% on the BER could be achieved. A space–frequency joint processing technique with low complexity was shown in [15] to suppress ICI and other interference in 2D. The ICI power as a function of the correlation of phase noise, channel correlation and frequency offset was derived in [16] using correlative coding. Loose bounds on the ICI power were briefly discussed. A new ICI-self-cancellation-scheme for OFDM systems was assessed in [17] in which improved performance was noted. An ICI cancellation method based on ICI matrix properties for UWB-OFDM systems was discussed in [18]. Improved performance was obtained for indoor environments and normalised frequency shifts. ICI reduction mechanism was considered as a combinatorial optimization problem in [19] in which two relaxation methods were proposed with encouraging results.

Even though the theoretical expression of $P_{\rm ICI}$ in terms of $f_{\rm d}T_{\rm s}$, ζ and ϵ was given, it is difficult to interpret and to visualise the behaviour of the $P_{\rm ICI}$. In fact, the final compact analytical expression of $P_{\rm ICI}$ cannot be obtained which motivated further work on deriving bounds on $P_{\rm ICI}$. It should be noted that the bounds reported in [1] as functions of $f_{\rm d}T_{\rm s}$ were derived based on Doppler spectrum $P(f)$. The bounds derived in this letter as functions of $f_{\rm d}T_{\rm s}$ and ζ are based on the scattering channel using its angle-of-arrival (AoA) probability density function (pdf) $p(\theta)$. Since $f_{\rm d}T_{\rm s}$ and ζ are important for the BS and the UE to compensate for Doppler spread respectively, it is necessary to examine bounds on $P_{\rm ICI}$ as functions of $f_{\rm d}T_{\rm s}$ and ζ, thus yielding more insight on $P_{\rm ICI}$.

The letter is organised as follows. Section 2 gives background on the universal bound derived in [1]. Section 3 derives the upper and lower bounds on $P_{\rm ICI}$ for a uniform scattering channel. Special cases when $\zeta = 0$ are also given. Section 4 further gives insight on the new bounds and compares them with the universal bound. Expressions of $f_{\rm d}T_{\rm s}$ and ζ to obtain a zero lower bound and to also lower the upper bound are derived. Section 5 concludes the main findings of the letter and also outlines possible further work.

2. Bounds based on $P(f)$

The $P_{\rm ICI}$ of an OFDM system with an infinite number of sub-carriers is defined as [1,20]

$$P_{\rm ICI} = \int_{-1}^{+1} (1-|x|)[1-r(T_{\rm s}x)]{\rm d}x = 1 - \int_{-1}^{+1}(1-|x|)r(T_{\rm s}x){\rm d}x, \qquad (1)$$

where $r(T_{\rm s}x)$ is the correlation function of the transmitted signal $x(t)$.

To determine the upper and lower bounds on $P_{\rm ICI}$, the limits of $1 - r(T_{\rm s}x)$ as given in Eq. (1) are required. In terms of $P(f)$, $1 - r(T_{\rm s}x)$ can be given as

$$\begin{aligned}1 - r(T_{\rm s}x) &= \int_{-f_{\rm d}}^{f_{\rm d}} P(f)[1-\exp({\rm j}2\pi f T_{\rm s}x)]{\rm d}f \\ &= 2\int_0^{f_{\rm d}} P(f)[1-\cos(2\pi f T_{\rm s}x)]{\rm d}f. \end{aligned} \qquad (2)$$

There are three main types of Doppler spectrum $P(f)$: (1) classical, (2) uniform, and (3) two-path, which are given as follows:

$$P_1(f) = \begin{cases} \frac{1}{\pi f_{\rm d}\sqrt{1-(f/f_{\rm d})^2}} & \text{if } |f| < f_{\rm d}, \\ 0 & \text{otherwise,} \end{cases} \qquad (3)$$

$$P_2(f) = \begin{cases} \frac{1}{2f_{\rm d}} & \text{if } |f| < f_{\rm d}, \\ 0 & \text{otherwise,} \end{cases} \qquad (4)$$

$$P_3(f) = \frac{1}{2}[\delta(f+f_{\rm d}) + \delta(f-f_{\rm d})]. \qquad (5)$$

The upper and lower bounds on $P_{\rm ICI}$ with respect to $P(f)$ given in Eqs. (3)–(5) were derived in [1] and are given here as

$$\frac{\alpha_1(2\pi f_{\rm d}T_{\rm s})^2}{12} - \frac{\alpha_2(2\pi f_{\rm d}T_{\rm s})^4}{360} \leqslant P_{\rm ICI} \leqslant \frac{\alpha_1(2\pi f_{\rm d}T_{\rm s})^2}{12}, \qquad (6)$$

where α_1 and α_2 are dependent on $P(f)$. For the classical model: $\alpha_1 = 1/2$ and $\alpha_2 = 3/8$, for the uniform model: $\alpha_1 = 1/3$ and $\alpha_2 = 1/5$, and for the two-path model: $\alpha_1 = \alpha_2 = 1$.

Since $\alpha_1 \leqslant 1$, the universal bound on $P_{\rm ICI}$ was also derived [1] and is given in Eq. (7) as

$$P_{\rm ICI} \leqslant \frac{(2\pi f_{\rm d}T_{\rm s})^2}{12} = \frac{\pi^2(f_{\rm d}T_{\rm s})^2}{3}. \qquad (7)$$

It should be noted that the universal bound given in Eq. (7) is applicable for any $P(f)$. The main aim of this paper is to derive the $P_{\rm ICI}$ bounds by evaluating $1 - r(T_{\rm s}x)$ as a function of $p(\theta)$ which is characterised by the scattering channel between the BS and the UE.

3. Bounds based on $p(\theta)$

From [21], the correlation function of the Jakes/Clarke 2D model with an AoA pdf $p(\theta)$ is given as [20]

$$r(T_{\rm s}x) = \frac{1}{2\pi}\int_{-\pi}^{+\pi} p(\theta)\exp[{\rm j}2\pi f_{\rm d}T_{\rm s}x\cos(\theta)]{\rm d}\theta, \qquad (8)$$

where $p(\theta) = A = 1/2\beta_m = 6/\pi$ [20] and β_m is the antenna beam width.

To incorporate the effects of the UE travelling direction ϵ and the frequency tracking ζ to compensate Doppler spread in the channel, Eq. (8) can be rewritten as [20]

$$r(T_{\rm s}x) = \frac{1}{2\pi}\int_{-\pi}^{+\pi} p(\theta)\exp\{{\rm j}2\pi f_{\rm d}T_{\rm s}x[\cos(\theta-\epsilon)-\zeta]\}{\rm d}\theta. \qquad (9)$$

From Eq. (9), we obtain

$$\begin{aligned}1 - r(T_{\rm s}x) &= \frac{1}{2\pi}\int_{-\pi}^{+\pi} p(\theta)\langle 1-\exp\{{\rm j}2\pi f_{\rm d}T_{\rm s}x[\cos(\theta-\epsilon)-\zeta]\}\rangle{\rm d}\theta \\ &= \frac{1}{2\pi}\int_{-\pi}^{+\pi} p(\theta)\langle 1-\cos\{2\pi f_{\rm d}T_{\rm s}x[\cos(\theta-\epsilon)-\zeta]\}\rangle{\rm d}\theta. \end{aligned} \qquad (10)$$

In addition, we have

$$\cos(u) = 1 - \frac{u^2}{2!} + \frac{u^4}{4!} - \cdots, \qquad (11)$$

thus

$$\frac{u^2}{2!} - \frac{u^4}{4!} \leqslant 1 - \cos(u) \leqslant \frac{u^2}{2!}, \qquad (12)$$

which are the bounds on $1 - \cos(u)$. It should be noted that the bounds given in Eq. (12) are only approximate as the most dominant terms in the infinite series of $\cos(u)$ are used. Thus, even though tight bounds on $P_{\rm ICI}$ were given in [1], there still exists some small degree of inaccuracy in the approximation which is also applied to the bounds derived in this letter. From Eq. (1), the $P_{\rm ICI}$ as a function of $f_{\rm d}T_{\rm s}$, ϵ and ζ is given as

$$\begin{aligned}P_{\rm ICI} = &\int_{-1}^{1}(1-|x|) \\ &\times\left\{\frac{1}{2\pi}\int_{-\pi}^{+\pi} p(\theta)\langle 1-\cos\{2\pi f_{\rm d}T_{\rm s}x[\cos(\theta-\epsilon)-\zeta]\}\rangle{\rm d}\theta\right\}{\rm d}x. \end{aligned} \qquad (13)$$

From Eqs. (10) and (12), substituting $u = 2\pi f_{\rm d}T_{\rm s}x[\cos(\theta-\epsilon)-\zeta]$, the upper and lower bounds on $P_{\rm ICI}$ can be derived as follows.