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Published in:
European Wireless 2017

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
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Symbol Error Outage Performance Analysis of MCIK-OFDM over Complex TWDP Fading

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Abstract—This paper investigates the instantaneous symbol error outage probability (ISEOP) of a Multicarrier Index Keying with Orthogonal Frequency Division Multiplexing (MCIK-OFDM) system using greedy detection, over Two-Way with Diffused Power (TWDP) fading channels. The closed-form expressions for the upper and lower bound on the ISEOP are derived to analyze the effects of TWDP and MCIK parameters on the outage performance of MCIK-OFDM. Through the numerical analysis and asymptotic case studies, we provide a new insight on the performance of MCIK-OFDM in a complex wireless propagation environment such as in Device-to-Device (D2D) communications that face a variety of fading conditions.

Index Terms—MICK-OFDM, TWDP fading, outage probability, symbol error probability (SEP), D2D communications.

I. INTRODUCTION

MCIK-OFDM or OFDM-IM (Index Modulation) [1] has recently been emerging as a promising candidate to improve the reliability and efficiency of the classical OFDM. Inspired on the Spatial Modulation (SM) concept, MCIK-OFDM conveys information bits on both the M-ary constellations and the indices of active subcarriers. In every transmission, only a subset of subcarriers is activated to carry the M-ary symbols and MCIK-OFDM structure compensates the loss of data caused by inactive subcarriers by additional bits carried by the indices of active subcarriers without any requirements of extra bandwidth or power. Moreover, it is easy for MCIK-OFDM to balance the trade-off between the spectral efficiency and reliability of systems just by switching on or off subcarriers. Thus, this scheme can provide a low-cost, low complexity and very flexible solution which is really needed for OFDM based D2D communications. All in all, MCIK-OFDM can be considered as a key technology for short-range wireless communication such as D2D or machine type communications (MTC).

Unlike traditional wireless systems, emerging machine-type D2D communication systems are expected to operate in non-conventional fading environments like enclosed metallic objects (e.g., in-vehicle, aircraft) and confined urban settings, which do not conform to the classical fading models such as Rayleigh and Rician. Recently, the generalized fading channel named the TWDP fading [2] has been proposed to characterize the widest range of fading behavior that includes the Rayleigh and Rician fading and the worse than Rayleigh fading scenarios. As a result, it is essential to analyze the performance of the MCIK-OFDM system over a variety of fading environments. However, most of existing papers have just considered MCIK-OFDM performance analysis with Rayleigh fading channels [1], [3]. The performance of MCIK-OFDM over the generalized TWDP fading has been first investigated in terms of the average pairwise error probability (PEP) [4]. To the best of our knowledge, the outage probability analysis in MCIK-OFDM has not been done in the literature.

This paper first investigates the outage performance of MCIK-OFDM in a variety of fading environments, employing the complex TWDP fading. By using the concept of instantaneous symbol error outage probability (ISEOP) [5], closed-form expressions for both the lower and upper bounds on the outage probability of MICK-OFDM using a low complexity detector are derived. It is shown that both the bounds are tight in low, moderate and high signal-to-noise ratio (SNR) regions. Using the derived expressions, the impacts of the generalized TWDP fading and MCIK-OFDM parameters on the ISEOP are numerically analyzed. The obtained numerical and asymptotic results allow a new insight into the outage performance of MCIK-OFDM in various D2D environments, especially demanding low-outage over the complex channel fading.

Notation: \( C(k, n) \), \([\cdot]\) respectively denote the binomial coefficient for \( n \) choose \( k \) and floor functions. Vectors and matrices are presented by lower-case bold and upper-case bold letters, respectively.

II. SYSTEM AND CHANNEL MODELS

A. System model

Consider an MICK-OFDM scheme with \( N_c = LG \) subcarriers that includes \( G \) subblocks of \( L \) subcarriers. In this scheme, for each subblock, only \( L \) out of \( N \) subcarriers are activated to carried information bits and \( N - L \) inactive subcarriers are zero padded. Hence, the information is conveyed on both \( M \)-ary constellation symbols with \( m_1 = L \log_2 M \) bits and the indices of active subcarriers with \( m_2 = \lfloor \log_2 C(L, N) \rfloor \), where \( C(L, N) \) is the total number of active subcarrier index combinations in every subblock. As a result, the total number of information bits in every MCIK-OFDM transmission is given by \( m = m_1 + m_2 \).

An MCIK-OFDM block is denoted by \( x = [x(1), \ldots, x(N)]^T \), with \( x(\hat{\alpha}) = 0 \) when subcarrier \( \hat{\alpha} \) is
inactive and \( x(\alpha) \in S \) when subcarrier \( \alpha \) is active, where \( \alpha, \tilde{\alpha} \in \{1, ..., N\} \) and \( S \) is the set of \( M \)-ary constellations. For a given active subcarrier \( \alpha \), each non-zero data symbol is transmitted with the power of \( \mathbb{E}\{\| x(\alpha) \|^2 \} = E_s N/L \), where \( N/L \) and \( E_s \) are the power allocation coefficient and the average power per \( M \)-ary symbol, respectively. Hereafter, for simplicity and without loss of generality, we just consider performance analysis of one subblock as each subblock operates independently.

The received signal is given by
\[
y = H x + n, \quad (1)
\]
where \( H = \text{diag}\{h(1), ..., h(N)\} \) is the channel matrix, where \( h(\alpha) \) denotes the channel coefficient corresponding to active subcarrier \( \alpha \) and for inactive subcarrier \( h(\tilde{\alpha}) = 0 \), and \( n = \{n(1), ..., n(N)\} \) presents additive white Gaussian noise (AWGN), with \( n(\alpha) \sim \mathcal{CN}(0, N_0) \).

B. TWDP fading model

Consider a TWDP fading channel [2] characterized by two typical parameters: \( K = (V_1^2 + V_2^2)/2\sigma^2 \) and \( \Delta = 2V_1/V_2 \), respectively denote the ratio between the specular and diffused power and the relative strength of two specular waves, where \( V_1 \) and \( V_2 \) present the envelopes of the two specular waves, and \( 2\sigma^2 \) is the average power of diffused waves. This generalized fading channel is capable of describing a large number of fading conditions from moderate to severe fading, in which the Rician PDF and Rayleigh PDF are the special cases of the TWDP probability density function (PDF) with appropriate choices of \( K \) and \( \Delta \) [2, Table III].

The cumulative distribution function (CDF) of the instantaneous signal-to-noise ratio (SNR) over the TWDP fading is given by [6]
\[
F_\gamma(x) = 1 - \frac{1}{2} \sum_{i=1}^{T} a_i \left\{ Q_1 \left[ \sqrt{2K(1 - \beta_i)}, \frac{2(1 + K)x}{\gamma} \right] + Q_1 \left[ \sqrt{2K(1 + \beta_i)}, \frac{2(1 + K)x}{\gamma} \right] \right\}, \quad (2)
\]
where \( T, a_i \) respectively denote the order of approximation of the PDF and the corresponding approximation coefficients as shown in [2, Table III], \( \beta_i = \Delta \cos \frac{\pi (i - 1)}{2T - 1}, \; \gamma = \frac{2\sigma^2(1+K)N E_s}{L N_0} \) is the average SNR at receiver, and \( Q_1(.) \) denotes the Marcum Q-function, given as follows
\[
Q_1(a, b) = \int_b^\infty xe^{-\frac{x^2 + a^2}{2}}I_0(ax)dx.
\]

III. OUTAGE PROBABILITY OVER TWDP FADING

For an outage-sensitive application, we now evaluate the outage probability performance over the complex TWDP fading, which allows to cope with a variety of wireless fading environments. For this, we employ the greedy detection [7], which exploits the strongest energy of received sub-carriers for index detection. We provide a new closed-form expression for the outage probability and its analysis for MCIK only and then MCIK-OFDM.

A. Outage probability of MICK

Let us first evaluate the outage probability of MCIK only. This is needed for a provision of the outage probability of the MCIK-OFDM later in this section. In MCIK, the information is only conveyed by the indices of active subcarriers, as a result, the symbol error event occurs when the active indices are incorrectly detected, leading to the instantaneous symbol error probability (SEP) of MCIK given by
\[
iSEP_{MCIK} = \frac{L}{N} \sum_{\alpha=1}^{N} v(\gamma_{\alpha}), \quad (3)
\]
where \( \gamma_{\alpha} = \bar{\gamma} | h(\alpha) |^2 \) is the instantaneous SNR per subcarrier and \( v(\gamma_{\alpha}) \) is the instantaneous pairwise error probability (PEP) of an event that an active subcarrier \( \alpha \) is incorrectly detected as the index of an inactive subcarrier \( \tilde{\alpha} \). Based on greedy method, the instantaneous PEP \( v(\gamma_{\alpha}) \) is independent of \( \tilde{\alpha} \), and is given as [7]
\[
v(\gamma_{\alpha}) = \sum_{i=1}^{N-L} \left( \frac{(-i)^{1}}{i+1} C(i,N-L) \right) e^{-\frac{i\gamma_{\alpha}}{2}}. \quad (4)
\]
Without loss of generality, let us have \( \gamma_1 \leq ... \leq \gamma_N \). Based on the ordered statistics, the CDF of \( \gamma_1 \) is given as
\[
F_{\gamma_1}(x) = 1 - \left( 1 - F_{\gamma_1}(x) \right)^N. \quad (5)
\]
Due to the fact that \( v(\gamma_1) = \max_{x=1, ..., N} \{ v(\gamma_{\alpha}) \} \), and based on (3), we deduce the following inequality
\[
\frac{L v(\gamma_1)}{N} \leq iSEP_{MCIK} \leq L v(\gamma_1). \quad (6)
\]
Using a tight approximation of \( v(\gamma_{\alpha}) \) [4], i.e., \( v(\gamma_{\alpha}) \approx \frac{N-L}{2N} e^{-\frac{\gamma_{\alpha}}{2}} \), a simplified formula for both the upper bound and lower bound of \( iSEP_{MCIK} \) in (3) is derived as follows
\[
\frac{L(N-L)}{2N} e^{-\frac{\gamma_{\alpha}}{2}} \leq iSEP_{MCIK} \leq \frac{L(N-L)}{2} e^{-\frac{\gamma_{\alpha}}{2}}. \quad (7)
\]
As shown in [5], an instantaneous symbol error outage event occurs when the instantaneous SEP is greater than a symbol error threshold \( P_{th} \). Given \( P_{th} \), the upper bound of the instantaneous symbol error outage probability (ISEOP) in the MICK system can be given by
\[
P_{out}^{MICK} = \Pr\{iSEP_{MCIK} \geq P_{th} \} \leq \Pr \left[ \frac{L(N-L)}{2} e^{-\frac{\gamma_{\alpha}}{2}} \geq P_{th} \right] = \Pr \left\{ \gamma_1 \leq \frac{MCIK}{\gamma_{th,up}} = 2 \ln \left[ \frac{L(N-L)}{2P_{th}} \right] \right\} = \frac{L}{1 - \left[ 1 - F_{\gamma_{\gamma_{MCIK}}} \right] N} \right\}. \quad (8)
\]
Finally, by using (2) and (8), the upper bound on the ISEOP is attained as
\[
P_{out,up}^{MCIK} = B \left( \gamma_{MCIK} \right), \quad (9)
\]
where $B(x)$ is defined as

$$B(x) = 1 - \left\{ \frac{1}{2} \sum_{i=1}^{T} a_i \right\} \left[ Q_1 \left( \sqrt{2}K(1-\beta)\sqrt{\frac{2(1+K)x}{\gamma}} \right) + Q_1 \left( \sqrt{2}K(1+\beta)\sqrt{\frac{2(1+K)x}{\gamma}} \right) \right]^N.$$

Similarly, the lower bound of the ISEOP in the MCIK system can be expressed as

$$P_{\text{ISEOP}}^{\text{MCIK}} = B(\gamma_{th,lo}^{\text{MCIK}}),$$

where $\gamma_{th,lo}^{\text{MCIK}} = 2\ln \left( \frac{4(N-L)}{2NP_0} \right).$

### B. Outage probability of MICK-OFDM

In MCIK-OFDM, M-QAM constellation symbols are carried on active subcarriers whose indices represent the MCIK symbol. Then, the instantaneous SEP of MCIK-OFDM can be formulated by using both the instantaneous PEP of the misdetection of the active subcarrier and the SEP of the M-ary QAM, i.e., $P_s \leq e^{-\left[\frac{1}{2}\sigma^2\gamma\right]^{\gamma}}$ [8], which can be formulated as

$$iSEP_{MO} \leq \frac{L}{N} \sum_{\alpha=1}^{N} \left\{ v(\gamma_{\alpha}) + [1 - v(\gamma_{\alpha})] e^{-\left[\frac{1}{2}\sigma^2\gamma\right]^{\gamma}} \right\},$$

where recall $v(.)$ in (4).

For simplicity in analysis, denote each element of the summation in (12) by $g(x)$, which is

$$g(x) = v(x) + [1 - v(x)] e^{-\left[\frac{1}{2}\sigma^2\gamma\right]^{\gamma}}.$$

Similarly to the previous sub-section, $\gamma_1 = \min_{\alpha} \left\{ \gamma_{\alpha} \right\}$ is employed to provide the upper bound and lower bound expressions for the instantaneous SEP of MCIK-OFDM, which can be given by

$$\frac{Lg(\gamma_1)}{N} \leq iSEP_{MO} \leq Lg(\gamma_1).$$

Note that, in the lower bound above, $Lg(\gamma_1)/N$ is just one term in the summation of (12), which corresponds to the instantaneous SEP with the minimum subcarrier SNR. Thus, $Lg(\gamma_1)/N$ must be less than $iSEP_{MO}$. Once again, using the approximation of $v(\gamma)$, i.e., $v(\gamma_{\alpha}) \approx \frac{N+L}{2} e^{-\frac{\gamma}{2\sigma^2}}$, the inequalities in (14) can be simplified as

$$\frac{\hat{g}(\gamma_1)}{N} \leq iSEP_{MO} \leq \frac{\gamma_1}{\gamma_1},$$

where

$$\hat{g}(x) = L \left\{ \frac{N+L}{2} e^{-\frac{\gamma}{2\sigma^2}} \left\{ 1 - e^{-\left[\frac{1}{2}\sigma^2\gamma\right]^{\gamma}} \right\} + e^{-\left[\frac{1}{2}\sigma^2\gamma\right]^{\gamma}} \right\}.$$

Accordingly, denote by $P_{\text{MO}}^{\text{out}}$ the ISEOP of MCIK-OFDM, i.e., $P_{\text{MO}}^{\text{out}} = \Pr \left[ iSEP_{MO} \geq P_{th} \right]$ for given $P_{th}$. Using (15)-(16), an upper bound and a lower bound on the ISEOP of the MCIK-OFDM system are expressed as

$$\Pr \left[ \frac{\hat{g}(\gamma_1)}{N} \geq P_{th} \right] \leq P_{\text{MO}}^{\text{out}} \leq \Pr \left[ \frac{\gamma_1}{\gamma_1} \geq P_{th} \right].$$

In general, a value for $x$ holding the equalities of $\hat{g}(x) = P_{th}$ and $\hat{g}(x) = P_{th}/N$ can not be obtained in closed-form for almost cases of $N$, $L$ and $M$ and thus, an iteration approach can be used to find out the roots of these equations. Instead, we now address a more effective method based on the approximate solutions, without the need of solving these two complicated equations.

Through the observation of $\hat{g}(x)$ in (16), we consider the following two cases:

**Case when $M \in \{2,4\}$ and large $\gamma$:** In this case, we have $\frac{3}{2(M-1)} \geq \frac{1}{\gamma}$. When $\gamma$ is large enough, we obtain the approximation of $\hat{g}(\gamma_{1}) \approx \frac{L(N-L)}{2NP_0} e^{-\frac{\gamma_1}{2\sigma^2}}$, with $\gamma_1 = \min_{\alpha} \left\{ \min_{\alpha} \left\{ \gamma_1 \right\} \right\}$. So in this case, the instantaneous SEP depends mainly on the accuracy of the index detection, and this leads to the two bounds of the ISEOP in MCIK-OFDM, given as

$$B(\gamma_{th,lo}^{\text{MCIK}}) \leq P_{\text{MO}}^{\text{out}} \leq B(\gamma_{th,up}^{\text{MCIK}}),$$

where $\gamma_{th,lo}^{\text{MCIK}}$ and $\gamma_{th,up}^{\text{MCIK}}$ are already defined in (8)-(11).

**Case when $M \in \{8,16,32,\ldots\}$ and large $\gamma$:** We obtain $\frac{3}{2(M-1)} \leq \frac{1}{\gamma}$ and, as a result, we devise $\hat{g}(\gamma_{1}) \approx \frac{L(N-L)}{2NP_0} e^{-\frac{\gamma_1}{2\sigma^2}}$ for large values of $\gamma$. This implies that when the M-ary modulation order is greater than 4, the instantaneous SEP of MCIK-OFDM is mainly influenced by the detection of M-ary symbols. Hence, the upper bound and lower bound on the ISEOP in MCIK-OFDM are described as

$$B(\gamma_{th,lo}^{\text{MO}}) \leq P_{\text{MO}}^{\text{out}} \leq B(\gamma_{th,up}^{\text{MO}}),$$

where $\gamma_{th,lo}^{\text{MO}} = \frac{2(M-1)}{4} \ln \left( \frac{L}{NP_0} \right)$ and $\gamma_{th,up}^{\text{MO}} = \frac{2(M-1)}{4} \ln \left( \frac{L}{NP_0} \right)$.

**Remark 1.** In all aforementioned schemes, the two bounds of ISEOP over TWDP can be expressed with the use of $B(\gamma_{th,up})$ and $B(\gamma_{th,lo})$, respectively, with $\gamma_{th,up} \in \left\{ \gamma_{MO}^{\text{MCIK}}, \gamma_{MO}^{\text{MCIK}} \right\}$, $\gamma_{th,lo} \in \left\{ \gamma_{MO}^{\text{MCIK}}, \gamma_{MO}^{\text{MCIK}} \right\}$. Referring to (10) and the definitions of $\gamma_{th,lo}$ and $\gamma_{th,lo}$ in (9)-(11)-(19), notice that for given $P_{th}$ and $N$, when $L$ increases from 1 to $N/2$, we observe that both $\gamma_{th,up}$ and $\gamma_{th,lo}$ increase while $\gamma$ in (2) decreases being proportional to $1/L$. This leads to a decrease in the Marcum Q function in (10). Thus, these observations provide an insight into that for given $P_{th}$ and $N$, both the bounds are proportional to $L \in [1, N/2]$.

Similarly, when $L$ continually increases from $N/2$ to $N$, $\gamma_{th,up}$ and $\gamma_{th,lo}$ are logarithmically decreasing for the MCIK as in (8) and (11), and logarithmically increasing for the MCIK-OFDM as in (19). Meanwhile, notice the fact that $\gamma$ decreases with $L$ faster than $\gamma_{th,up}$ and $\gamma_{th,lo}$. This makes the Marcum Q function in (10) decrease. Finally, we can conclude that for given $N$, the larger the number of active subcarriers is, the worse the outage performance of the MICK or MCIK-OFDM system is in a variety of TWDP fading conditions.

### IV. Special Cases

**A. Rayleigh fading**

The TWDP fading becomes Rayleigh fading when $K = 0$. By substituting $K = 0$ into (10) and using the fact that $Q_1(0,x) = \exp(-x^2/2)$, the closed-form expression for
both the upper bound and lower bounds on the ISEOP over the Rayleigh fading can be given with respect to the unified thresholds $\gamma_{th,lo}$ and $\gamma_{th,up}$ by

$$1 - \exp \left( - \frac{N\gamma_{th,lo}}{\bar{\gamma}} \right) \leq P_{out}^{Ray} \leq 1 - \exp \left( - \frac{N\gamma_{th,up}}{\bar{\gamma}} \right)$$ (20)

As seen in (20), the lower-bounded (or upper-bounded) outage probability over Rayleigh fading is increasing with the ratio of $\gamma_{th,lo}/\bar{\gamma}$ (or $\gamma_{th,up}/\bar{\gamma}$). It is worth mentioning that within this ratio, the threshold values corresponding to either MCIK or MCIK-OFDM increases with $L$ observed in the previous section. This implies that for given $N$ and $P_{th}$, small values for $L$ are better choice to produce lower ISEOP over Rayleigh fading conditions.

### B. Rician fading

When $K > 0$ and $\Delta = 0$, TWDP fading becomes the Rician fading with only one single dominant specular component. Similarly, using (10), we can easily obtain the two bounds on the ISEOP over Rician fading as follows

$$1 - Q_1^N \left[ \sqrt{2K} \frac{2(K+1)\gamma_{th,lo}}{\bar{\gamma}} \right] \leq P_{out}^{Ric} \leq 1 - Q_1^N \left[ \sqrt{2K} \frac{2(K+1)\gamma_{th,up}}{\bar{\gamma}} \right].$$ (21)

As seen in (21), both the bounds are determined by the unified ratios ($\gamma_{th,lo}/\bar{\gamma}$ and $\gamma_{th,up}/\bar{\gamma}$) as well as $N$ and $K$.

### V. Numerical Results and Discussion

In this section, the simulation results are used to verify the accuracy of the closed-form expressions for the upper bound and lower bound on the ISEOP of MCIK-OFDM using greedy detection, over various TWDP fading scenarios.

Fig. 1 illustrates the upper bound and lower bound on the ISEOP over the TWDP, Rician and Rayleigh fading of two MCIK-OFDM systems with $(N, L, M) = (4, 1, 2), (4, 2, 16)$, that corresponds to two cases in (18)-(19). It is shown that the upper bound is very close to the corresponding lower bound in all cases of fading conditions, with the gap between them around 1 dB at all values of the outage probability. This reveals the tightness of proposed bounds. Therefore, it is important to realize that the outage performance in MCIK-OFDM mainly depends on the worst channel among $N$ subcarriers.

Fig. 2 shows the upper bounds on the outage probability of MCIK-OFDM systems with $N = 8$ and various values of $L$. We can see from this figure that the outage probabilities increase when the number of active subcarriers $L$ increases for a given value of $N$. This successfully confirms the accuracy of the conclusion presented in remark 1, in the section III.

Fig. 3 compares the ISEOP of MCIK-OFDM and classical OFDM with the same spectral efficiency per subblock of $N = 4$ subcarriers. The upper bound on the ISEOP of classical OFDM is given as (19), but with another threshold of SNR that is given by $\gamma_{OFDM}^{th} = \frac{2(M-1)}{3} \ln \left( \frac{N}{P_{th}} \right)$. It is illustrated via Fig. 3 that the outage performance of MCIK-OFDM outperforms that of classical OFDM, with an SNR gain of approximately 2 dB on almost SNR regions.

Fig. 4 shows the upper bound on the ISEOP of a MCIK-OFDM system versus various values of TWDP parameters at $\bar{\gamma} = 30$ dB. It is clear that the smaller value of $\Delta$ provides the better outage performance, especially when $K$ is large. However, when $K$ is very small, i.e., $K = -\infty$ dB, it is shown via Fig. 4 the ISEOP does not depend on $\Delta$, this is true since the TWDP fading becomes the Rayleigh in this case. Furthermore, when $\Delta$ tends to 1 and $K$ is large enough, TWDP will offer the worse performance than the Rayleigh fading.
Fig. 3. The ISEOP (upper bound) of MCIK-OFDM and classical OFDM over the TWDP ($K = 10, \Delta = 1$) with $N = 4, L = 1, 3, M = 2, 4$, and $P_{th} = 10^{-3}$.

Fig. 4. The ISEOP (upper bound) of MCIK-OFDM versus the various values of $K, \Delta$ with $(N, L, M) = (4, 1, 2), \bar{\gamma} = 30dB$ and $P_{th} = 10^{-3}$.

VI. CONCLUSIONS

We have analyzed the outage performance of MCIK-OFDM based on the instantaneous SEP with the derivations of the closed-form expressions for the upper and lower bounds on the ISEOP, over TWDP fading conditions. These two bounds are very close, which helps us gain an insight of the effects of the generalized TWDP fading and MCIK-OFDM parameters on the outage performance. This will be useful to evaluate the performance of MCIK-OFDM and design this system over various complex fading conditions including moderate, severe and worse than Rayleigh fading, especially in the context of D2D communications.

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