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***Abstract*—A novel Layered Division Multiplexing (LDM) With Index Modulation (LDM-IM) system is proposed in this paper. It employs the Index Modulation (OFDM-IM) technology to enhance the transmission performance of the original LDM system by transmitting extra bits through the Orthogonal Frequency Division Multiplexing (OFDM) subcarriers indices. The proposed system is based on a two-layer, Upper Layer (UL) and Lower Layer (LL), LDM system that serves two independent data services for at least two User Equipment(s) (UE) simultaneously. Besides this, by exploiting the Index Modulation (IM), each UE can receive the extra bits by decoding the subcarriers activation patterns. To map the extra bits to the subcarriers, a simple random codebook is designed in the proposed system based on the concept of OFDM-IM. To proof the availability and reliability of the proposed system, two metrics are chosen to evaluate the system performance, the average Symbol Error Rate (SER) and the transmission rate. In this paper, the architecture of the proposed system is introduced firstly. After that, the average SER of it is analyzed and verified by the Monte Carlo simulation. Finally, the transmission rate of the proposed system and the original LDM system is compared and evaluated.**

***Index Terms*—LDM, OFDM-IM, Advanced Television Systems Committee (ATSC) 3.0, Pairwise Error Probability (PEP), SER, Spectral Efficiency**

I. INTRODUCTION

To achieve higher spectral efficiency in the 5G system, many novel cutting edge technologies have been proposed. One of the most popular is the Power-Domain Non-Orthogonal Multiple Access (NOMA) (PD-NOMA), which can simultaneously serve multiple users in the same frequency channel. The key concepts of it are the superposition coding and Successive Interference Cancellation (SIC) [1]. Another technology inspired by the PD-NOMA, Layered Division Multiplexing (LDM), has been proposed for the next generation digital TV broadcasting system to expand the capacity of delivering the multimedia services to a variety of the UEs simultaneously [2]. In the ATSC 3.0 standard, a two-layer LDM structure has been accepted to utilize two different power levels, UL and LL [3]. These two layers can separately provide High Definition TV (HDTV) services for mobile devices with Quadrature Phase-shift keying (QPSK) modulation and Ultra-High Definition TV (UHDTV) service for TVs with 64-Quadrature Amplitude Modulation (QAM) or 256-QAM [3]–[5].

In [2], the two-layer LDM system utilizes the injection level to define the power level of LL signal relative to that of UL signal. The injection level decides the power coefficients of two layers and the range of coefficients is [0, 1). In this system, the UL is allocated with a higher power, while that of LL is lower. The transmit signal is generated as the superposition of the signals from two layers. At the receiver side, if the UE requires the UL signal, it can treat the LL signal as interference and detects the received signal by using by the Maximum Likelihood (ML) estimation. However, if the UE requires the LL signal, it needs to cancel the UL signal by SIC technology before LL detection. The greatest advantage of LDM, comparing to the traditional Time-Division-Multiplexing (TDM) and Frequency-Division-Multiplexing (FDM), is that it offers a significant capacity gain with a slightly complex system design [6]. Another advantage of LDM is that it can easily be combined with other technologies to achieve higher performance. Such as, in [7], the author analyzed the capacity of the LDM system with Multiple-Input-Multiple-Output (MIMO) technology. In [8], the author proposed a Spatial Modulation (SM) technology aided the LDM system, called SM Aided LDM (SM-LDM).

Apart from technologies like PD-NOMA and LDM, OFDM-IM technology also provides a novel concept to expand the OFDM modulation into another dimension. It exploits the indices of subcarriers as an information bearer to transmit extra bits [9]. For the index of subcarrier encoding and decoding, a lookup table is maintained or a combinatorial method is used in the OFDM-IM system to map a set of bits to a group of subcarrier indices [10]. Assume a lookup table used in the OFDM-IM system, at the transmitting side, it actives the specific subcarriers based on a piece of bits, called index bits, which is extracted from the input bits. The rest of the input bits are modulated and transmitted through the active subcarriers. At the receiving side, the indices of active subcarriers need be detected firstly. And then, the indices can be used to decode the index bits by the lookup mapping table. In the meantime, the received symbols carried by the subcarriers are demodulated to bits. After that, the complete bits can be recovered by combining the index bits with the demodulated bits. With this feature, the OFDM-IM can easily extend the traditional In-phase And Quadrature (IQ) modulation to three dimensions: amplitude, phase and indices of active subcarriers [11], [12]. To improve the performance of OFDM-IM in subsequent studies, the researchers are mainly focused on two directions. One is to find methods to optimize the subcarriers selection to reach better error performance, such as [13], [14]. Another one is to improve the modulation and combination of index bits and bits for modulation to enhance the performance, such as [15]–[17].

To make further improvement of spectral efficiency of the LDM system and the OFDM-IM system, a LDM-IM system is proposed in this paper. The main contributions are summarized below:

- The LDM system with OFDM Index Modulation is proposed for the first time. Moreover, to verify the availability and reliability of this system, a simulation of the proposed system is implemented.
- The approximate average SER of the proposed system is analyzed in closed form expression with the approximate Q-function.
- The average SER analysis is verified by the Monte Carlo simulation, and the transmission performance of the proposed is compared with the original LDM system.

For the rest of this paper, the architecture and system blocks design is introduced in section II. After that, the average SER analysis of the proposed system is provided in section III and verified in section IV. Additionally, in this section, the transmission performance of the proposed system and the original LDM is compared. The summaries are discussed in section V.

II. LDM-IM SYSTEM

A. System Framework

The block diagrams of transmitter and receiver are shown in Fig. 1. The simulation of the proposed system is implemented based on these two diagrams. Besides of them, in the simulation, a frequency-selective slow Rayleigh Fading channel is considered as the channel model and a two-layer power structure is exploited to serve two UEs with individual input bits [18], [19]. The injection level between two layers is assumed larger enough to avoid interference between each other. In addition, the Cyclic Prefix (CP) is configured long enough to ensure all subcarriers are orthogonal [20]. At the receiver side, assuming all active subcarriers patterns can be decoded successfully, the Channel State Information (CSI) $\tilde{\mathbf{H}}$ and the codebook CB are already known [21].

B. Index Modulation

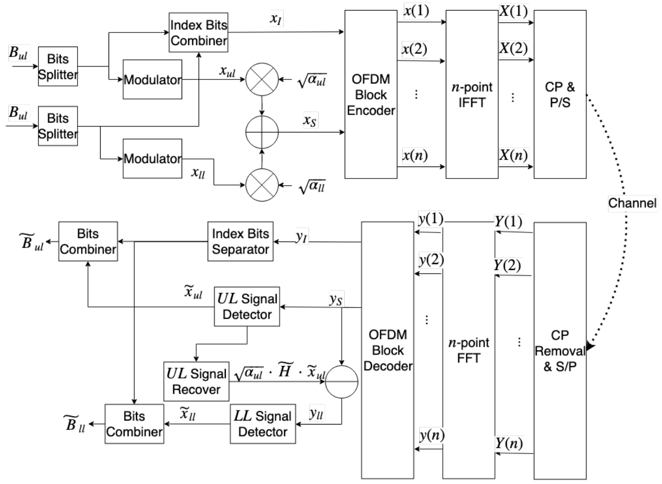

Fig. 1. Block diagram of the LDM-IM

TABLE I
AN EXAMPLE THE $N = 4$ CODEBOOK DESIGN

Order	Bits	Index	Active channels	Tx
1	[0,0]	1	[0,0,0,1]	[0,0,0,x]
2	[0,1]	2	[0,0,1,0]	[0,0,x,0]
3	[1,0]	3	[0,1,0,0]	[0,x,0,0]
4	[1,1]	4	[1,0,0,0]	[x,0,0,0]

In this paper, a simple subcarrier index mapping method is selected for the index modulation in the proposed system. Assuming N is the number of subcarriers and $\mathbf{x}_I$ is the bits required for the index modulation, the maximum number of $\mathbf{x}_I$ can be calculated by $\lfloor \log_2(N) \rfloor$, where $\lfloor \cdot \rfloor$ is the floor function. A codebook *CB* is designed to represent $\mathbf{x}_I$, and the number of possible patterns in it can be given by $|\mathit{CB}| = 2^{\lfloor \log_2(N) \rfloor}$. Because two layers need to share the $\mathbf{x}_I$, the available bits for UL can be calculated by $\lfloor \log_2(N) \rfloor / 2$ and the rest bits are for LL. The M_{ul} and M_{ll} modulation schemes, such as Binary Phase Shift Keying (BPSK), QPSK or M-QAM, can be adopted for UL and LL separately, the transmission rate in Bits Per Channel Use (BPCU) equals to

$$R_{bpcu} = \lfloor \log_2(N) \rfloor + (\log_2(M_{ul}) + \log_2(M_{ll})). \quad (1)$$

For further explanation of the codebook design, an example of the codebook for $N = 4$ subcarriers is described in the following. Because of $N = 4$, the number of $\mathbf{x}_I$ is $\lfloor \log_2(4) \rfloor = 2$ and the number of possible patterns is $|\mathit{CB}| = 2^2 = 4$. Then, the codebook can be designed as shown in Table I.

As descriptions above, comparing with the original LDM system, the proposed system apparently increases the number of transmitting bits.

C. Signal Transmission

At transmitter side, for both UL and LL, their input bits should be divided into two segments. One is used for the index modulation and the other is used for the digital modulation. The modulated symbols for UL and LL can be denoted by x_{ul} and x_{ll}. By injecting the symbols of LL into that of UL, the injected symbols can be represented by

$$\mathrm{x}_S(k) = \sqrt{\alpha_{ul}}\mathrm{x}_{ul}(k) + \sqrt{\alpha_{ll}}\mathrm{x}_{ll}(k) \quad (2)$$

where $k = 0, 1, ..., K-1$, K is number of symbols and the α_{ul} and α_{ll} are defined as relative coefficients of transmitting power of LL and UL. The coefficients can be given by

$$\alpha_{ul} = \frac{1}{1 + 10^{\frac{\Delta_{inj}}{10}}}, \alpha_{ll} = \frac{10^{\frac{\Delta_{inj}}{10}}}{1 + 10^{\frac{\Delta_{inj}}{10}}} \quad (3)$$

where the injection level $\Delta_{inj} = SNR_{UL} - SNR_{LL}$ and the sum of two coefficients equals to 1.

Before the transmission, it is necessary to map the injected symbols $\mathrm{x}_S(k)$ to the active subcarriers. Then, a vector $\mathbf{v}$ is adopted to express a subcarriers pattern that is

$$\mathbf{v} = [\upsilon(0), \upsilon(1), ..., \upsilon(N-1)]^T \tag{4}$$

where $(\cdot)^T$ denotes the transpose operator of a matrix and $\upsilon(n) \in \{0, 1\}, n = 0, 1, ..., N-1$. The 0 and 1 are represented the inactive and active state of the ith subcarrier, respectively. Then, the OFDM blocks can be expressed by

$$\mathbf{x} = [x(0), x(1), ..., x(N-1)]^T \tag{5}$$

where the element of the OFDM blocks is

$$x(n) = \begin{cases} \mathrm{x}_S(k) & \text{if } \upsilon(n) = 1 \\ 0 & \text{if } \upsilon(n) = 0 \end{cases} \tag{6}$$

where $k = 0, 1, ..., K-1$. After that, the OFDM blocks will be converted into time domain by the N-point Inverse Fast Fourier transform (IFFT) and transformed to serial sequence with patched CP.

D. Signal Reception

At the receiver side, after converting Serial-To-Parallel (S/P), removing CP and performing Fast Fourier transform (FFT), the received OFDM blocks can be expressed as

$$\mathbf{y} = \sqrt{\frac{P}{N}}\mathbf{H}\mathbf{x} + \mathbf{w} \tag{7}$$

where P is the total transmit power, which is assumed that the power is equally distributed to N subcarriers, and the channel response is denoted as $\mathbf{H} = \mathrm{diag}[h(0), h(1), ..., h(N-1)]$ that is a $N \times N$ diagonal matrix. The $\mathbf{w} = [w(0), w(1), ..., w(N-1)]$ is the vector of N independent complex Additive White Gaussian noise (AWGN), and the noise on each subcarrier is $w(k) \sim \mathcal{N}(0, N_0)$, where N_0 is the noise power. Due to the frequency-selective slow Rayleigh Fading channel and its channel gain to be exponentially Independent and Identically Distributed (i.i.d) with mean λ^{-1}, the Probability Density Function (PDF) can be given by

$$f(x) = \lambda e^{-\lambda x}. \tag{8}$$

At the receiver side, the $\mathbf{y}_I$ and $\mathbf{y}_S$ can be easily obtained by the codebook and the indices. Besides of this, because the LL signal is treated as an additional interference [2], the received signal $\mathbf{y}_S$ can be considered as the $\mathbf{y}_{ul}$ signal of UL. And with the ML detection, the detected symbols of UL can be given by

$$\tilde{\mathbf{x}}_{ul} = \underset{\hat{\mathbf{x}} \in \Theta_{ul}}{\mathrm{argmin}} \, ||\mathbf{y}_{ul} - \sqrt{\frac{P_{ul}}{N}}\tilde{\mathbf{H}}\hat{\mathbf{x}}|| \tag{9}$$

where $\mathrm{argmin} \, || \cdot ||$ is to obtain the minimum value from the norm set, Θ_{ul} denotes the set of all constellation points by the UL modulation scheme and P_{ul} is the transmitting power of UL given by

$$P_{ul} = \alpha_{ul} P. \tag{10}$$

The $\tilde{\mathbf{x}}_{ll}$ can be also detected by the ML method after cancelling the recovered UL signal from $\mathbf{y}_S$. The function for SIC can be expressed as

$$\mathbf{y}_{ll} = \mathbf{y}_{ul} - \sqrt{\frac{P_{ul}}{N}}\tilde{\mathbf{H}}\tilde{\mathbf{x}}_{ul}. \tag{11}$$

The ML method used for LL detection is

$$\tilde{\mathbf{x}}_{ll} = \underset{\hat{\mathbf{x}} \in \Theta_{ll}}{\mathrm{argmin}} \, ||\mathbf{y}_{ll} - \sqrt{\frac{P_{ll}}{N}}\tilde{\mathbf{H}}\hat{\mathbf{x}}|| \tag{12}$$

where Θ_{ll} denotes the set of all constellation points by the LL modulation scheme and the transmitting power of LL P_{ll} is

$$P_{ll} = \alpha_{ll} P. \tag{13}$$

After UL and LL detection, $\tilde{B}_{ul}$ and $\tilde{B}_{ll}$ can be completed by combining the UL and LL segments of $\mathbf{y}_I$ to $\tilde{\mathbf{x}}_{ul}$ and $\tilde{\mathbf{x}}_{ll}$ segments separately.

III. ERROR PERFORMANCE ANALYSIS

A. PEP for UL

According to (2) and (7) in section II, the received signal of the UL can be expressed as

$$y_{ul} = \left(\sqrt{\frac{P_{ul}}{N}}x_{ul} + \sqrt{\frac{P_{ll}}{N}}x_{ll}\right)h_{ul} + w_{ul}. \tag{14}$$

Because the conditional PEP is defined as the probability of incorrect estimated symbol $\check{x}_{ul}$ of the transmitted symbol x_{ul}, the conditional PEP of UL can be defined as follows

$$\begin{aligned} &Pr\left(x_{ul} - \check{x}_{ul} | h_{ul}\right) = \\ &Pr\left(|y_{ul} - \sqrt{\frac{P_{ul}}{N}}h_{ul}\check{x}_{ul}|^2 \geq |y_{ul} - \sqrt{\frac{P_{ul}}{N}}h_{ul}x_{ul}|^2\right) \end{aligned} \tag{15}$$

where $x_{ul} \neq \check{x}_{ul}$. By combining (14) and (15) and setting $\check{\Delta}_{ul} = x_{ul} - \check{x}_{ul}$, the conditional PEP can be expressed as (16), at the top of next page. Because w_{ul} is normally distributed with zero mean and $\frac{\sigma^2}{2}$ variance, the decision variance in (16) is Gaussian distribution $2\Re\{h_{ul}\check{\Delta}_{ul}w_{ul}\} \sim \mathcal{N}\left(0, 2|h_{ul}|^2|\check{\Delta}_u l|^2\sigma^2\right)$. According to the Q-function definition, if Y is Gaussian random variable and $Y \sim \mathcal{N}\left(\mu, \sigma^2\right)$[22]

$$Pr\left(Y \geq y\right) = Q\left(\frac{y - \mu}{\sigma}\right) \tag{17}$$

where μ is mean and σ^2 is variance. Then, the conditional PEP can be expressed as

$$Pr\left(x_{ul} - \hat{x}_{ul} | h_{ul}\right) = Q\left(-\frac{\sqrt{\gamma_{ul}}\beta_{ul}}{\upsilon_{ul}}\right), \tag{18}$$

where $\gamma_{ul} = |h_{ul}|^2$,

$$\beta_{ul} = \sqrt{\frac{P_{ul}}{N}}|\check{\Delta}_{ul}|^2 + 2\Re\{\sqrt{\frac{P_{ll}}{N}}x_{ll}\check{\Delta}_{ul}\} \tag{19}$$

and

$$\upsilon_{ul} = \sqrt{2}|\check{\Delta}_{ul}|\sigma. \tag{20}$$

$$Pr\left(x_{ul}-\check{x}_{ul}|h_{ul}\right)=Pr\left(2\Re\{h_{ul}\check{\Delta}_{ul}w_{ul}\}\geq-|h_{ul}|^{2}\left(\sqrt{\frac{P_{ul}}{N}}|\check{\Delta}_{ul}|^{2}+2\Re\{\sqrt{\frac{P_{ll}}{N}}\check{\Delta}_{ul}x_{ll}\}\right)\right) \tag{16}$$

To simply the process of Q-function, the approximated Q-function can be given by [13]

$$Q\left(x\right)\approx\frac{1}{12}\mathrm{exp}\left(-\frac{x^{2}}{2}\right)+\frac{1}{4}\mathrm{exp}\left(-\frac{2x^{2}}{3}\right). \tag{21}$$

To evaluate the unconditional PEP for UL, the conditional PEP needs to be averaged over the PDF. With the PDF of $\gamma_{ul}=|h_{ul}|^{2}$ and the approximated $Q(-\frac{\sqrt{\gamma_{ul}}\beta_{ul}}{v_{ul}})$, the approximated unconditional PEP can be represented by

$$\begin{aligned}&Pr\left(x_{ul}-\check{x}_{ul}\right)=\int_{0}^{\infty}f\left(\gamma_{ul}\right)Q\left(-\frac{\sqrt{\gamma_{ul}}\beta_{ul}}{v_{ul}}\right)\mathrm{d}_{\gamma_{ul}}\approx\\&\lambda\left(12\lambda+6\left(-\frac{\sqrt{\frac{P_{ul}}{N}}|\check{\Delta}_{ul}|^{2}+2\Re\{\sqrt{\frac{P_{ll}}{N}}x_{ll}\check{\Delta}_{ul}\}}{\sqrt{2}|\check{\Delta}_{ul}|\sigma}\right)^{2}\right)^{-1}+\\&\lambda\left(4\lambda+\frac{8}{3}\left(-\frac{\sqrt{\frac{P_{ul}}{N}}|\check{\Delta}_{ul}|^{2}+2\Re\{\sqrt{\frac{P_{ll}}{N}}x_{ll}\check{\Delta}_{ul}\}}{\sqrt{2}|\check{\Delta}_{ul}|\sigma}\right)^{2}\right)^{-1}\end{aligned} \tag{22}$$

where $\Re\{\cdot\}$ denotes to obtain the real part of a complex number.

B. PEP for LL

Due to the (11), the received signal of LL can be expressed as

$$y_{ll}=\left(\sqrt{\frac{P_{ll}}{N}}x_{ll}+\sqrt{\frac{P_{ul}}{N}}\hat{\Delta}_{ul}\right)h_{ll}+w_{ll} \tag{23}$$

where $\hat{\Delta}_{ul}$ is the residual interference by the SIC from the UL signal.

By following the same steps as the PEP for UL in subsection III-A, the conditional PEP for LL can be given by

$$Pr\left(x_{ll}-\check{x}_{ll}|h_{ll}\right)=Q\left(-\frac{\sqrt{\gamma_{ll}}\beta_{ll}}{v_{ll}}\right) \tag{24}$$

where the channel gain $\gamma_{ll}=|h_{ll}|^{2}$,

$$\beta_{ul}=\sqrt{\frac{P_{ll}}{N}}|\check{\Delta}_{ll}|^{2}+2\Re\{\sqrt{\frac{P_{ul}}{N}}\hat{\Delta}_{ul}\check{\Delta}_{ll}\} \tag{25}$$

where $\check{\Delta}_{ll}=x_{ll}-\check{x}_{ll}$, and

$$v_{ll}=\sqrt{2}|\check{\Delta}_{ll}|\sigma. \tag{26}$$

With the PDF of $\gamma_{ll}=|h_{ll}|^{2}$ and the approximated $Q(-\frac{\sqrt{\gamma_{ll}}\beta_{ll}}{v_{ll}})$, the unconditional PEP for LL can be expressed by

$$\begin{aligned}&Pr\left(x_{ll}-\check{x}_{ll}\right)=\int_{0}^{\infty}f\left(\gamma_{ll}\right)Q\left(-\frac{\sqrt{\gamma_{ll}}\beta_{ll}}{v_{ll}}\right)\mathrm{d}_{\gamma_{ll}}\approx\\&\lambda\left(12\lambda+6\left(-\frac{\sqrt{\frac{P_{ll}}{N}}|\check{\Delta}_{ll}|^{2}+2\Re\{\sqrt{\frac{P_{ul}}{N}}\hat{\Delta}_{ul}\check{\Delta}_{ll}\}}{\sqrt{2}|\check{\Delta}_{ll}|\sigma}\right)^{2}\right)^{-1}+\\&\lambda\left(4\lambda+\frac{8}{3}\left(-\frac{\sqrt{\frac{P_{ll}}{N}}|\check{\Delta}_{ll}|^{2}+2\Re\{\sqrt{\frac{P_{ul}}{N}}\hat{\Delta}_{ul}\check{\Delta}_{ll}\}}{\sqrt{2}|\check{\Delta}_{ll}|\sigma}\right)^{2}\right)^{-1}\end{aligned} \tag{27}$$

IV. SIMULATION RESULTS

In this section, the analysis of average SER provided in section III is verified by a Monte Carlo simulation firstly. And then, the transmission rate of the proposed and the original LDM systems is compared and discussed. In this simulation, the UE1 and the UE2 are configured to receive the UL signal and LL signal independently and separately. The injection level between UL and LL is set to -15 dB. The BPSK is used for both UL ($M_{ul}=2$) and LL ($M_{ll}=2$). The channel gain γ_{ul}, γ_{ll} and noise power N_0 are normalized to 1.

A. Average SER Analysis Verification

For the verification, a simulation is performed to obtain the average SER of the proposed system with different transmit power per subcarrier P_{sub}/N_0. The simulation results are presented in Fig. 2. The results depict the average of SER performance for UE1 and UE2 with $\sigma=1$ and $\lambda=1$. From the figure, it can be noticed that the derived PEP expressions for UL and LL, given by (22) and (27), are verified by the simulation results because of the good approximation. Moreover, from Fig. 2, the UE1 has the better error performance than the UE2 that because the transmit power allocated to UE1 is larger than the power to UE2, when the UEs have same channel gain.

Besides of IM part, the proposed system is exactly same as the original LDM system, so these results are also applicable to the LDM.

B. Transmission Performance Comparison

To compare the transmission performance of the proposed system to the original LDM system, the transmit bits per channel of the proposed system and the original LDM are compared. Fig. 3 illustrates the correlation between the transmission rate and the number of subcarriers N. As it can be noted from the figure, along with increasing N, the transmission rate of the proposed system raises obviously faster than that of the original LDM system, that is because the proposed

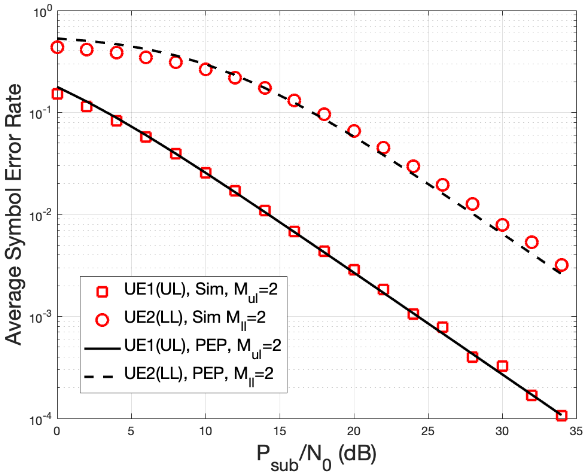

Fig. 2. Average SER vs Transmit Power, $\sigma = 1$ and $\lambda = 1$

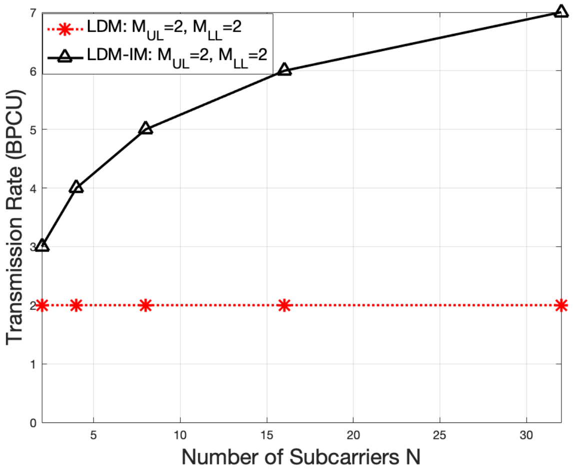

Fig. 3. Transmission Rate (BPCU) vs Number of Subcarriers

system can exploit the indices of subcarriers to deliver extra bits, and according to (1), the larger N is, the more extra bits can be delivered.

V. CONCLUSION

In this paper, a novel system, LDM-IM, was proposed to provide a higher spectral efficiency based on the original LDM-OFDM system. The architecture and system models of the proposes system were introduced in details firstly. And then, the average SER of the system for UL and LL were analyzed separately in section III. Subsequently, the analysis was verified by the Monte Carlo simulation in section IV. Meanwhile, the comparison results of transmission rate proofed that the proposed system can provide a higher transmission performance without any loss of error performance compared to the original LDM system.

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