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Abstract

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Abstract *We propose to use Han-Kobayashi (HK) coding and dirty-paper coding (DPC) to cope with inter-carrier interference (ICI) in dual-carrier transmissions. We show the considerable benefit of those methods to increase throughput in presence of strong ICI for dense carrier spacing.*

Introduction

Rapid demand of the data-rate increase has necessitated high-throughput technologies, such as faster-than Nyquist[1,2] and super-channel transmissions[3–5], where each transceiver operates independently while increasing the total throughput without increasing the processing speed. The spectrum efficiency may increase as the carrier spacing decreases. However, inter-carrier interference (ICI) can be a major limiting factor to realize a dense carrier spacing, and ICI is often desired to be minimized.

For overlapped dual-carrier transmissions, we can model the system as a 2-user interference channel. Han and Kobayashi have shown[6] that a very strong interference cannot limit the channel capacity because interference conveys data sent from the adjacent channel and those message can be decoded for strong interference cases. This theory suggests that suppressing undesired interference may not always be the best solution. Even for weak interference cases, the best known rate is achieved by the Han-Kobayashi (HK) scheme[6–8], which uses a super-position coding and a successive decoding.

In this paper, we study a potential benefit obtained by the HK scheme for dual-carrier transmissions. In addition, we compare the achievable rate of joint decoding and dirty-paper coding (DPC)[9,10]. The major contributions are twofold: i) we analyze the benefit of HK scheme for different filter parameters, and ii) we investigate the impact of equalizer memory length in dual-carrier transmissions. To the best of authors' knowledge, there has been no literature which applied HK or DPC to optical communications.

Interference in dual-carrier transmissions

Fig. 1 depicts a schematic of dual-carrier coherent optical transmissions, employing the HK scheme. Two transmitters send coded-modulation messages s_1 and s_2, respectively, at carrier frequencies f_1 and f_2. Letting B be the baud rate, the carrier spacing normalized by the baud rate is written as $\delta f = (f_2 - f_1)/B$. For simplicity, we assume root raised-cosine (RRC) filters with a roll-off factor of α for both Tx and Rx filters. We consider the case when the carrier spacing is dense such that $\delta f < 1+\alpha$, leading to ICI as shown in Fig. 2, where $\delta f = 0.85$ and $\alpha = 0.2$.

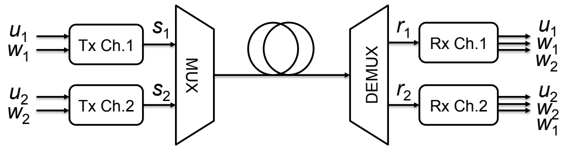

Fig. 1: Dual-carrier transmission systems with HK scheme.

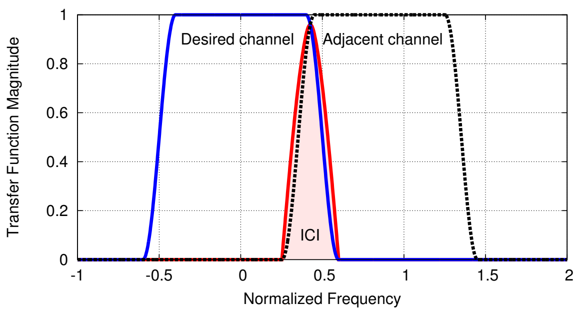

Fig. 2: Transfer functions in overlapped dual-carrier transmissions.

For a carrier f_k ($k \in \{1,2\}$), the receiver obtains r_k, passing through optical fibers and TRx filters. This system can be '*conceptually*' modeled as

$$r_1 = s_1 + \sqrt{\beta}\, s_2 + n_1, \tag{1}$$

$$r_2 = \sqrt{\beta}\, s_1 + s_2 + n_2, \tag{2}$$

where β is a ratio between interference and desired signal powers, and n_k is an additive Gaussian noise with a variance of $1/\rho$ for a signal-to-noise power ratio (SNR) of ρ. Since in reality the ICI signal has memory and phase rotation, this simplified model will be modified and discussed in more detail later.

Han-Kobayashi coding and decoding

The HK scheme[6–8] uses super-position coding and partial joint decoding. For transmitters, the coded sequence s_k is a super-position of two codewords of source messages u_k and w_k. One is for private messages, which are decoded only at the intended receiver. The other is used for public messages, which are decoded at receivers for both carriers. Two codewords (for private u_k and public messages w_k) are superposed with a power splitting of λ_k and $1-\lambda_k$.

The achievable data rate of HK scheme for a symmetric power splitting case $\lambda_1 = \lambda_2$ is given[8] by

$$R_{\mathrm{HK}} = \begin{cases} 2C\left(\frac{\rho}{1+\beta\rho}\right), & \rho \le \rho_1, \\ 2C\left(\frac{(\beta^2\rho+\beta-1)(1-\beta)+\beta\rho}{1+\beta(\beta^2\rho+\beta-1)}\right), & \rho_1 < \rho \le \rho_2, \\ C\left(\frac{1-\beta}{2\beta}\right) + C\left(\frac{(1+\beta)^2\rho-(1-\beta)}{2}\right), & \rho_2 < \rho, \end{cases}$$

where $\rho_1 = \frac{1-\beta}{\beta^2}$, $\rho_2 = \frac{1-\beta^3}{\beta^3(\beta+1)}$, and $C(\rho) = \log_2(1+\rho)$. When allowing an asymmetric power splitting with $\lambda_1 = 0$ and $\lambda_2 > 0$, slightly higher data rates in high SNR regimes can be achieved[8].

For the case when all messages are private with $\lambda_1 = \lambda_2 = 1$ (corresponding to a conventional coding method), the achievable rate reduces to

$$R_{\mathrm{conv}} = 2C\left(\frac{\rho}{1+\beta\rho}\right). \quad (3)$$

On the contrary, for the case when the all messages are public with $\lambda_1 = \lambda_2 = 0$ (i.e., joint decoding scheme), the achievable rate becomes

$$R_{\mathrm{joint}} = \begin{cases} 2C\left(\frac{\rho}{1+\beta\rho}\right), & \rho \le \rho_1, \\ C\left((1+\beta)\rho\right), & \rho_1 < \rho. \end{cases} \quad (4)$$

When one transmitter knows the message of the other transmitter, we can use the DPC scheme[9] to cancel the interference in advance like Tomlinson-Harashima precoding, achieving the rate:

$$R_{\mathrm{DPC}} = C(\rho) + C\left(\frac{\rho}{1+\beta\rho}\right). \quad (5)$$

One transmitter requires twice-times higher processing speed to use DPC. Note that a practical DPC based on repeat-accumulate codes is reported by Erez and ten Brink[10].

Memory of inter-channel interference

The model of ICI should be modified by taking the memory of the interference impulse response into account, as shown in Fig. 3, where the impulse response magnitude of the ICI component is plotted for $\alpha \in \{0.2, 0.05\}$ and $\delta f = 0.85$. It is seen that the impulse response of the desired signal has no inter-symbol interference (ISI) at a sample of symbol timing because of the Nyquist criterion. Although the peak power of the impulse response for ICI is lower than the desired signal, ICI has longer memory especially for a smaller roll-off factor.

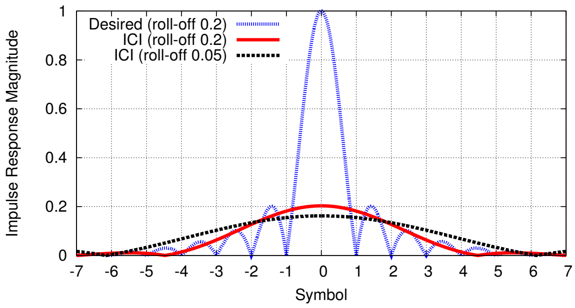

Fig. 3: Impulse response magnitude of desired and interference signals ($\alpha = \{0.2, 0.05\}$, $\delta f = 0.85$).

Therefore, we need an equalizer to decode interference signals for HK, DPC and joint decoding. Let L and $h(z)$ be the equalizer memory length and the discrete-time complex-valued impulse response of ICI signal, respectively. Using a finite-memory maximum *a posteriori* probability (MAP) equalization, the signal power within the memory $\sum_{k=-L/2}^{L/2} |h(k)|^2$ contributes to the interference power in β, and the reminder outside of the memory adds up the noise variance $1/\rho$.

Performance analysis

We evaluate the performance of HK and DPC in dual-carrier transmissions. To obtain spectrum efficiency, the achievable sum rates (R_{HK}, R_{conv}, R_{joint}, and R_{DPC}) are normalized by a total bandwidth consumption of $B(1+\alpha+\delta f)$.

Fig. 4 shows the throughput as a function of roll-off factor α for 3-tap and 19-tap equalizers at a noise spectrum density of -30 dBc and a carrier spacing of $\delta f = 0.85$. We can see that a conventional scheme (which does not consider ICI) degrades with the increased roll-off factor because of the increasing noise and interference power. For 3-tap equalizers, the throughput can be increased with HK, DPC and joint decoding particularly at around $\alpha = 0.6$. For 19-tap long-memory equalizers, HK and DPC provide a significant gain at around $\alpha = 0.2$. It should be noted that minimizing ICI with $\alpha = 0$ is not optimal for those schemes.

At a roll-off factor of $\alpha = 0.2$, the performance curves against the carrier spacing δf are plotted

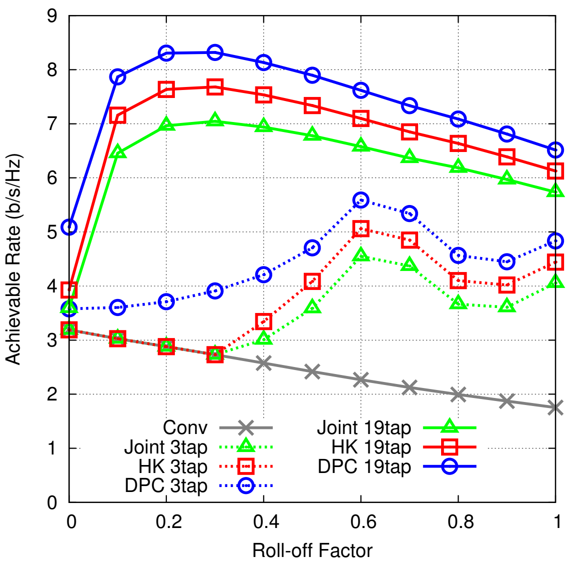

Fig. 4: Achievable rate vs. roll-off factor α ($\delta f = 0.85$).

in Fig. 5. For low ICI regimes such that $\delta f > 1$, there is few gain of the HK scheme. Whereas, the HK, DPC and joint decoding can achieve $2 \sim 5$ times higher throughput than conventional scheme in strong ISI regimes when long-memory equalizers are used.

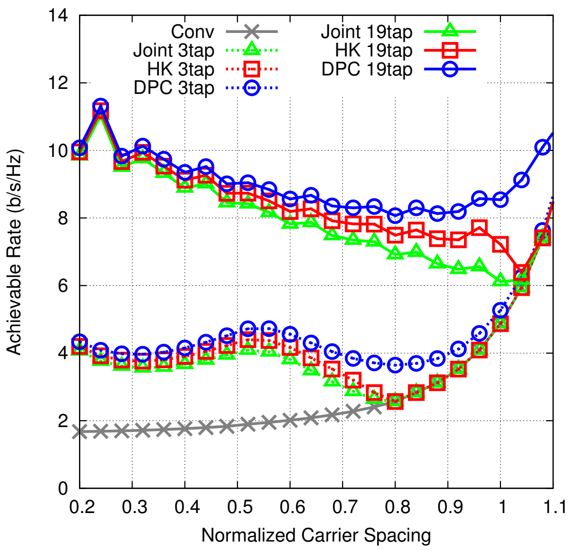

Fig. 5: Achievable rate vs. carrier spacing δf ($\alpha = 0.2$).

The impact of the equalizer memory is shown in Fig. 6. It is demonstrated that the longer memory offers better performance with HK, and that less than 5-tap memory cannot outperform the conventional way. It is because the ICI signal cannot be decoded with shorter-memory equalization than the memory of ISI impulse response especially for small roll-off factor cases.

Conclusions

We have shown a significant benefit of HK scheme to deal with ICI in dual-carrier transmissions. Compared to a conventional scheme,

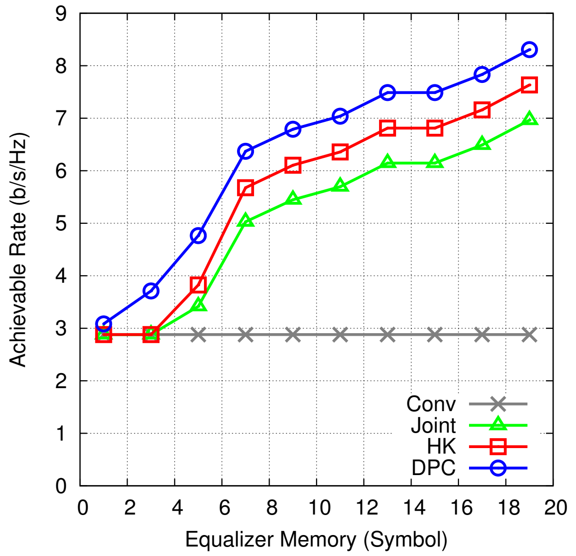

Fig. 6: Achievable rate vs. equalizer memory ($\alpha = 0.2$, $\delta f = 0.85$).

HK scheme achieves approximately twice higher throughput for the case of overlapped carrier spacing with long-memory equalizers. We have also compared with DPC and joint decoding, respectively showing a slightly better and worse performance than HK scheme. The generalization to multiple carriers and detail evaluation in nonlinear fiber channels remain as a future work. With nonlinearity, HK may be more useful because ICI can increase.

Acknowledgments

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