Laser Frequency Drift Compensation with Han-Kobayashi Coding in Superchannel Nonlinear Optical Communications

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Laser Frequency Drift Compensation with Han–Kobayashi Coding in Superchannel Nonlinear Optical Communications

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Introduction

The demand of high-speed data rates in optical communications has brought advanced technologies including superchannel transmission[1–6], where parallel transmitters send independent data using different wavelengths to increase total throughput. The spectral efficiency increases as the channel spacing decreases. However, inter-channel interference (ICI) can be a major limiting factor to realize dense channel allocation.

In order to handle ICI in superchannel transmissions, we have proposed to use Han–Kobayashi (HK) coding[6], which showed significant gain in spectral efficiency in the presence of strong ICI for super-dense sub-Nyquist channel spacings. It was expected that the HK coding will enable increased robustness to other practical hardware imperfections such as laser frequency drift and mistuning, which can cause probabilistic ICI even for quasi-Nyquist channel spacings.

This paper studies the gain of the HK coding in the presence of laser frequency drift. We show that the spectral efficiency can be improved by the HK coding, especially when a large deviation of laser frequency is present. This may reduce requirements for laser frequency stabilization, leading to lower complexity and power consumption.

Superchannels with laser frequency drift

We consider a superchannel transmission system with $N_{\text{ch}} = 3$ subchannels. Fig. 1 shows an example of power spectrum of superchannel signals for the case when the channel spacing normalized by baud rate B is $\delta f = 1.01$ so that no ICI is present with a root-raised-cosine (RRC) filter of rolloff factor 0.01. Although such a quasi-Nyquist system achieves the highest spectral efficiency, the system can be readily suffered from some hardware imperfections such as laser frequency drift. It is shown in Fig. 1 that undesired ICI across adjacent subchannels can occur if the transmitter (Tx) laser frequency is deviated from the nominal case. For simplicity, we assume that the laser frequency is randomly drifted by following the Gaussian distribution with a standard deviation of $\sigma_f B$.

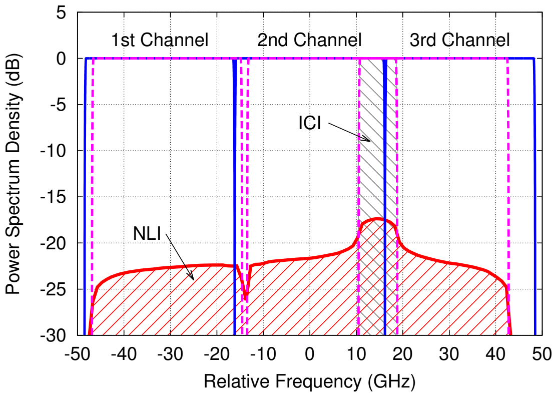

Fig. 1: Spectrum example of superchannel transmission in presence of laser frequency drift ($\delta f = 1.01, \sigma_f = 0.1$). Blue solid line: nominal Tx spectrum, pink dashed line: deviated Tx spectrum due to frequency drift, black-shaded area: possible ICI, red-shaded area: NLI computed by GN model[7].

As shown in Fig. 1, nonlinear interference (NLI) caused by Kerr fiber nonlinearity also deviates according to Tx spectrum. Here, the NLI spectrum is calculated by the Gaussian noise (GN) model[7]. Since the NLI can be non-identical for different subchannels, rate adaptation[5] and/or power control[4] have been studied to improve performance. Without such rate/power controls, the achievable rate of the conventional coding scheme can be constrained by the worst subchannel as follows:

$$R_{\text{conv}} = N_{\text{ch}} \min_k \left[C\Big(\frac{\rho_k \beta_{k,k}}{1 + \rho_k \sum_{i \neq k} \beta_{i,k}} \Big) \right], \qquad (1)$$

where $C(x) = \log_2(1+x)$, ρ_k is the signal-to-noise ratio at the k-th subchannel, and $\beta_{i,k}$ corresponds to a power fraction from the i-th Tx subchannel to the k-th receiver (Rx) subchannel, defined as

$$\beta_{i,k} = \frac{\int \big| G_{\text{rrc}}(f - f_i^{\text{tx}}) H_{\text{cd}}(f) G_{\text{rrc}}(f - f_k^{\text{rx}}) \big|^2 \mathrm{d}f}{\int \big| G_{\text{rrc}}(f - f_k^{\text{nom}}) H_{\text{cd}}(f) G_{\text{rrc}}(f - f_k^{\text{nom}}) \big|^2 \mathrm{d}f},$$

where $G_{\text{rrc}}(f)$ and $H_{\text{cd}}(f)$ denote transfer functions of the RRC filter and chromatic dispersion, respectively. Here, f_k^{tx}, f_k^{rx}, and f_k^{nom} are carrier frequencies for the Tx laser, Rx laser, and nominal case, respectively, at the k-th subchannel. Because frequency drifts occur at both Tx and Rx lasers (i.e., $f_k^{\mathrm{tx}} \neq f_k^{\mathrm{rx}}$ with high probability), the desired signal power can be also deviated as $\beta_{k,k} < 1$. The ICI from the i-th subchannel to the k-th subchannel can appear when the Tx and Rx filters overlap each other as $\beta_{i,k} > 0$ for $i \neq k$.

Han–Kobayashi (HK) superchannel coding

To deal with ICI caused by the laser frequency drift, we consider superchannel optical transmission systems employing the HK coding scheme[6], as shown in Fig. 2. The HK scheme splits data at each Tx subchannel into two portions; one is private data u_n for only the intended Rx, and the other data w_n is public for all Rx's. These two data are superimposed with a certain power splitting ratio λ_n. At each Rx subchannel, all public data are jointly decoded, and intended private data is decoded after ICI cancellation. Unintended public data (i.e., w_i for $i \neq n$ at the n-th Rx subchannel) are discarded in the end.

By controlling the power splitting ratio λ_n, the HK scheme can achieve joint decoding gain for public data while mitigating ICI for private data. The achievable sum rate is expressed as follows:

$$
\begin{aligned}
R_{\mathsf{HK}} = {} & \sum_k C\Big(\frac{\rho_k \lambda_k \beta_{k,k}}{1+\rho_k \sum_{i\neq k} \lambda_i \beta_{i,k}}\Big) \\
& + \min_k \Big[C\Big(\rho'_k \sum_i \bar{\lambda}_i \beta_{i,k}\Big), \sum_j C\Big(\rho'_k \bar{\lambda}_j \beta_{j,k}\Big), \\
& \qquad \min_j \Big\{ C\Big(\rho'_k \bar{\lambda}_j \beta_{j,k}\Big) + C\Big(\rho'_k \sum_{i\neq j} \bar{\lambda}_i \beta_{i,k}\Big) \Big\} \Big],
\end{aligned}
$$

where $\bar{\lambda}_k = 1-\lambda_k$ and $\rho'_k = \rho_k/(1+\rho_k \sum_i \lambda_i \beta_{i,k})$. The first term of R_{HK} comes from the private data u_n after ICI cancellation, and the reminder corresponds to joint decoding of public data w_n.

System parameters

We assume $B = 32$ Gbaud per channel and RRC filter with a rolloff factor of $\alpha = 0.01$. The normalized channel spacing δf is chosen from $0.5 \leq \delta f \leq 1.2$. We use the GN model[7] to calculate NLI power spectrum after $N_{\mathsf{s}} = 15$ spans of standard single-mode fiber (SSMF), whose span length is 80 km, dispersion parameter is 16.5 ps/nm/km, fiber loss is 0.2 dB/km, and nonlinear coefficient is 1.3 /W/km. Amplified spontaneous emission noise is calculated, assuming that Erbium-doped fiber amplifier (EDFA) with a noise figure of 4 dB compensates for every span loss. The theoretical analysis is carried out by calculating NLI according to randomly deviated laser frequencies. The achievable sum rate is normalized by a nominal superchannel bandwidth of $B(1+\alpha+\delta f(N_{\mathsf{ch}}-1))$.

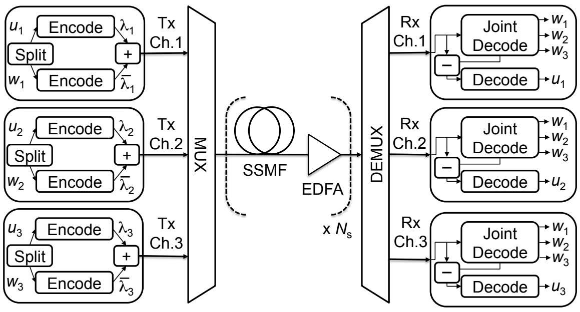

Fig. 2: Superchannel optical communications with Han–Kobayashi coding for ICI management.

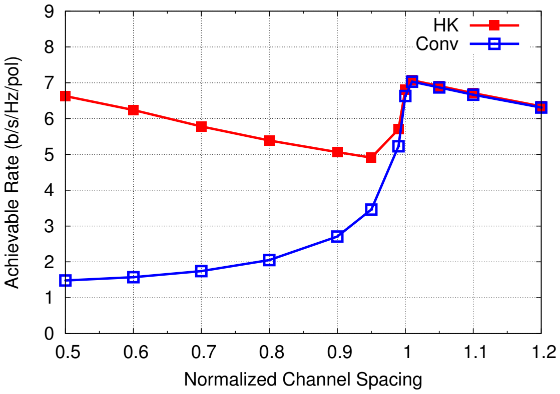

Fig. 3: Nominal spectral efficiency as a function of normalized channel spacing δf with no laser frequency drift.

Performance results

Fig. 3 shows the achievable rate as a function of channel spacing δf, for the nominal case without frequency drifts. It is shown that the spectral efficiency is maximized at a quasi-Nyquist spacing of $\delta f = 1.01$. Although the HK coding can compensate for ICI at sub-Nyquist spacings of $\delta f < 1$, the achievable rate cannot be higher than the zero-ICI cases. However, the quasi-Nyquist spacing may be susceptible to laser frequency drifts. In fact, the laser frequency can drift by a few GHz due to aging and other effects if no frequency stabilizer other than temperature controller is used.

Fig. 4 shows the outage probability of achievable rates at a channel spacing of $\delta f = 1.01$ in the presence of laser frequency drifts with a standard deviation of $\sigma_f = 10, 1, 0.1\%$. We can see that the achievable rate is significantly degraded as the standard deviation σ_f increases. Fig. 5 shows the achievable rate as a function of launch power for $\delta f = 1.01$ and $\sigma_f = 1\%$. For achieving an outage probability below 1%, the HK coding is advantageous to compensate for the loss caused by laser

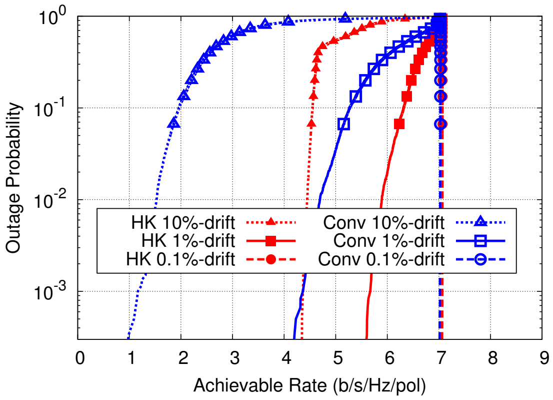

Fig. 4: Outage probability of achievable rate in presence of laser frequency drift ($\delta f = 1.01, \sigma_f = 0.10, 0.01, 0.001$).

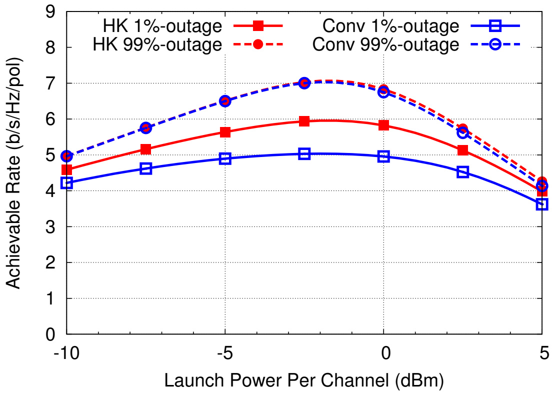

Fig. 5: Achievable rate as a function of launch power in presence of laser frequency drift ($\delta f = 1.01, \sigma_f = 0.01$).

frequency drifts even for quasi-Nyquist spacings. Note that practical systems require more stringent outage probability below 10^{-7}. It is expected from Fig. 4 that the gain of the HK coding can be higher for lower outage probabilities.

Figs. 6 and 7 show the achievable rates for 1% outage as a function of laser frequency deviation σ_f and normalized channel spacing δf, respectively. The conventional scheme at a quasi-Nyquist spacing of $\delta f > 1$ showed considerable rate degradation for a frequency deviation above $\sigma_f > 0.3\%$. Note that the HK coding at a sub-Nyquist spacing of $\delta f = 0.7$ can outperform the low-density spacing cases at $\delta f > 1$ in the presence of a large laser frequency drift of $\sigma_f = 10\%$.

Conclusions

We analyzed the impact of laser frequency drift on the achievable rate for superchannel optical communications. It was shown that the HK coding scheme can provide improved robustness against ICI caused by the laser frequency drift, achieving 2-times higher rate than conventional scheme. In addition, sub-Nyquist 70% spacing can maintain 5 b/s/Hz/pol spectral efficiency, and outperform quasi-Nyquist systems at a 10% standard deviation of laser frequency. Such high robustness to the drift may reduce the complexity and power consumption for laser frequency stabilization.

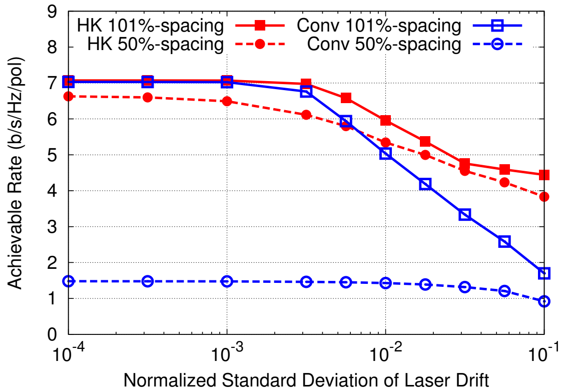

Fig. 6: Achievable rate for 1% outage as a function of laser frequency deviation σ_f ($\delta f = 0.50, 1.01$).

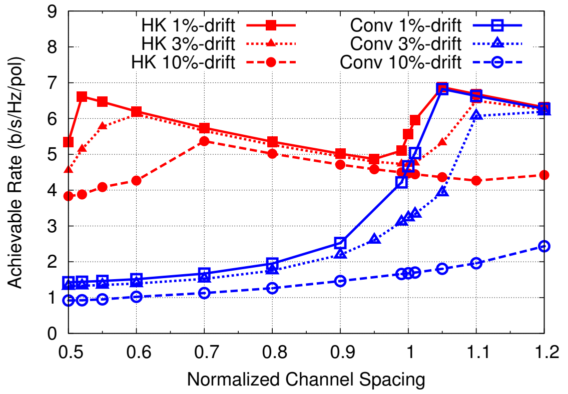

Fig. 7: Achievable rate for 1% outage as a function of normalized channel spacing δf ($\sigma_f = 0.1, 0.03, 0.01$).

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