Characterization, Modelling and Measurement of Device Imperfections in Advanced Coherent Transceivers

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Abstract *Device imperfections turn to be the dominant impairment for high speed, high order modulation transceivers. For both linear and nonlinear imperfections, the characterization, modelling, and measurement method are reviewed. There are various methods for linear imperfections, whereas the nonlinear imperfections need more research.*

Introduction

Currently, the dominant application of optical coherent transmission is the metro network and inter-data-centre network. In such scenario, the transmission imperfections, such as fibre nonlinear effect, are much less than that in long haul application, whereas the device imperfections in transceiver turn important. Furthermore, current transmission uses high baud rate, such as 192 Gbaud[1], and high order modulation format, such as 256-QAM[2]. In such system, the device imperfections turn much severe and dominate the transmission performance. As a result, the transceiver device imperfections need to be well modelled, characterized, and measured.

In this paper, we review the progresses in device imperfection modelling, characterization and measurement. Both linear and nonlinear distortions are discussed. The measurement method with and without instruments are discussed.

Overview of transceiver linear imperfection and measurement

The linear distortion is the basic imperfection in a communication system. In principle, the frequency transfer fuciton sufficiently characterizes the linear effect. Taking one polarization tributary in coherent transmitter as an example, Fig. 1 shows the actual device for in-phase (I) and quadrature-phase (Q) branch are different. As a result, a full descprition should use 2x2 real transfer fuction which handles I and Q branch separately, rather than 1x1 complex transfer function[3] . It could also be considerd as the common part of I and Q branch and the difference part of I and Q branch. The difference between I and Q branch is named as IQ imbalance. It includes frequency independent amplitude imbalance, phase imbalance and skew, and frequenc depedent IQ imbalance[4]. IQ imbalance causes the frequency image distortion and is the most significant linear distortion in transceivers[5].

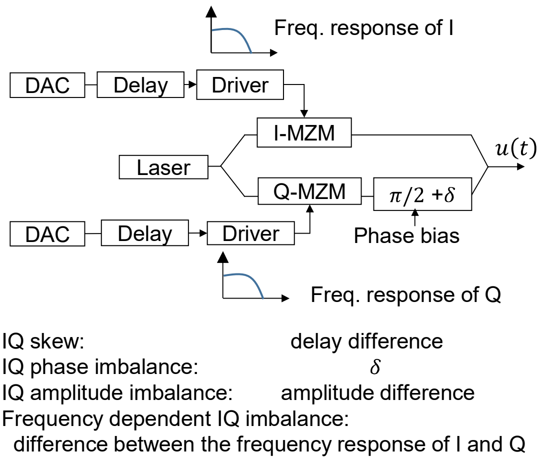

Fig. 1 Linear imperfections in coherent transceiver, taking one polarization tributary of transmitter as an example

After the modelling and characterization, measurement of those imperfections is another important task. There exist three different scenarios. In the first scenario, the measurement instrument, such as high-resolution optical spectrum analyser, electrical vector analyser, could be used. With the help of instruments, the device imperfections could be measured accurately. In fact, this always occurs in laboratory experiment and occasionally occurs in the factory.

The second scenario is in field pre-service measurement where high functional instrument cannot be used. This is very important for the real product. Since it is pre-service measurement, there is the freedom to design the stimulus to the transceiver. Using this functionality, it is possible to design the measurement process that only use transceiver itself or use some additional device. There have been lots of excellent work for this topic and we will introduce them later.

The third scenario is in field in-service measurement, where we only have very limited freedom to design the training sequence. This usually belongs to the monitor technology. The

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basic idea is to assume the adaptive equalizer compensates the imperfections and to analyse the equalizer coefficient thereafter [6]. We do not touch this technology further in this paper.

Linear imperfections in receiver

The issue of device linear imperfections in receiver is less significant compared with that of transmitter because there always has ***adaptive*** linear equalizer in digital signal processing (DSP) to compensate them. The receiver frequency independent IQ amplitude and phase imbalance could be obtained by the standard Gram-Schmidt orthogonalization procedure [7]. The IQ skew could be obtained by analysing the I and Q branch beating signal when a tunable continuous waveform laser is injected into the receiver[8]. If the white ASE noise is injected into the receiver, the frequency amplitude response of each tributary could be obtained straightforwardly. The phase response and the frequency dependent phase imbalance are more challenging and there are some solutions [9],[10].

Linear imperfections in transmitter

If we could use instrument, such as high-resolution optical spectrum analyser, the device imperfection measurement is not difficult. For example, after the digital flat spectrum Nyquist signal is send to one branch, the frequency amplitude response of that branch could be obtained by measuring the output optical spectrum [11]. Then, the IQ amplitude imbalance could be simply obtained by comparing that of I and Q branch. To measure the IQ phase imbalance and IQ skew, single side band digital comb is used. The frequency image component measured by optical spectrum analyser contains the information of IQ phase imbalance and IQ skew [12].

Measurement without instrument is much more challenging. The preferred technology only uses the transmitter itself. No additional high cost devices/functions, such as high speed photo diode (PD), analog to digital converter, and DSP, are used.

The frequency amplitude response of each branch could be separately measured by transmitter built-in low speed monitor PD [13]. As shown in Fig. 2, the average optical power after modulation $P_{av,i}$ has a fixed one-to-one relationship with electrical driver signal amplitude $AG(f_i)$, where A is the amplitude of digital tone, and $G(f_i)$ is the frequency amplitude response to be measured. In the 1st step, we fix the frequency f_i to low value f_0 where $G(f_0) = 1$, and chang the digital amplitude A. Then, the relationship between the average power P_{av}, and $AG(f)$ is calibrated. In the 2nd step, we set $A = 1$, and sweep f_i, and measure the average power $P_{av,i}$. Employing the calibrated relation in step 1, the frequency amplitude response $G(f_i)$ is measured.

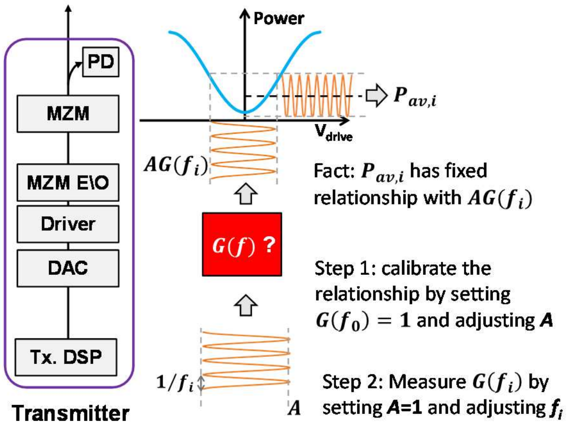

Fig. 2 Tx frequency amplitude response measurement by Tx bulit-in low speed monitor PD

The frequency phase response of each branch could also be separately measured by low speed PD and low speed DSP [14]. As shown in Fig. 3, the stimulus is the fixed interval ($d\omega$ =1GHz) digital two-tone signal and the phase of the two tones are synchronized. After Tx phase response, the phases changes to $\theta(\omega_{n+1})$ and $\theta(\omega_n)$. The square detection of low-speed PD beats the two tones and filter out high frequency components. Obviously, the low frequency component of $d\omega$ contains the information of $\theta(\omega_{n+1}) - \theta(\omega_n)$ because it is the beating signal. Then the low speed synchronizing detection obtains the group delay at ω_n.

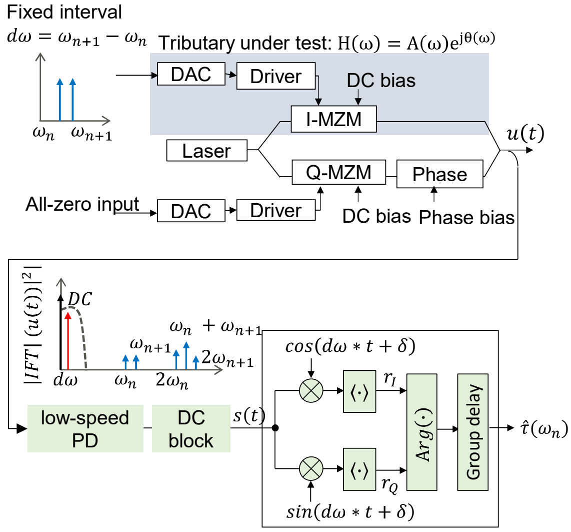

Fig. 3 Tx frequency phase response measurement by Tx bulit-in low speed monitor PD

The frequency dependent IQ phase imbalance could be measured by low speed PD and DSP [15]. In that approach, one tone ω_n of the two-tone signal is injected to I branch, and the other tone

$\omega_{n+1} = \omega_n + d\omega$ is injected to Q branch. After the beating process in the low speed PD, the $d\omega$ component contains the information of frequency dependent IQ phase imbalance.

If additional devices, high speed DSP, golden coherent receiver, and other functions are allowed, there would be more solutions. By sending the IQ interleaved multi-tone stimulus, the transceiver frequency response and IQ-skew can be simultaneously measured with the help of golden coherent receiver [16]. The phase retrieval approach could monitor frequency dependent IQ imbalance with the assistance of high speed PD and ADC [17]. The delay interferometer, high speed balanced PD, and high speed ADC are used to measure the frequency dependent IQ imbalance by employing elaborate IQ stimulus [18].

Model of device nonlinearity

The device nonlinear imperfection is another kind of important distortion. It is much more complex than the linear imperfection. There are lots of open issues to be solved.

Volterra series is the fundamental modelling for general nonlinear device [19]. The Volterra coefficients, or kernels, could be learned from device input and output waveform. One important trick is the learned model not only depends on device setting, input signal power, but also depends on input signal format [20]. The noise like signal, such as orthogonal frequency division multiplexing signal, is the safe selection.

Volterra series is very complicated. The number of terms increases with nonlinear order and memory length exponentially. There are various simplified Volterra model to balance the accuracy and the complexity [21]. The simplest one is memoryless nonlinear polynomial model.

Some model employs the physical nonlinear mechanism. For example, the Mach-Zehnder modulator naturally has sinusoidal function. In electrical circuit, such as the electrical driver, the capacitor may change with the applied voltage [22]. The plasma dispersion effects in Si-based modulator leads to nonlinear voltage-phase response and parasitic amplitude modulation [23].

Characterization of device nonlinearity

There have various specifications to characterize the nonlinear effect itself, such as total harmonic distortion (THD), 3rd order intermodulation, noise power ratio (NPR) and so on. The problem is there is no good correlation between system BER and those specifications.

Regarding THD, the frequency of input signal is usually limited by the scope of spectrum analyser. Thus, THD at high frequency is hard to be measured. However, the frequency dependency of nonlinear characteristic could be as large as 40dB in coherent transceiver [24].

NPR is another widely used one [25]. To measure NPR, a specific frequency component is notched at the input and the corresponding frequency component is measured at the output. Since any linear effect does not generate new frequency component, the notch frequency component at the output is considered as nonlinear noise. However, as shown in Fig. 4, the system Q estimated from NPR does not agree with the actual Q of the nonlinear system when input signal is not Gaussian [26].

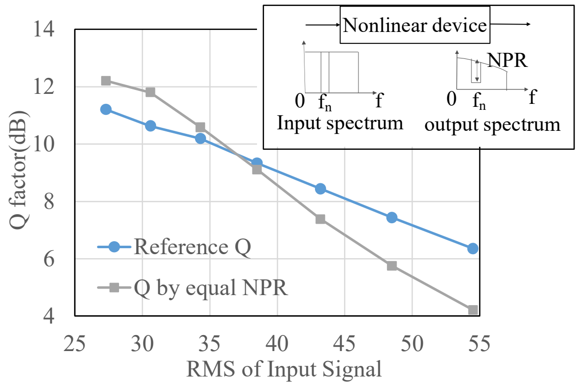

Fig. 4 The Q factor estimated from NPR does not agree with the real Q. Inset shows the definition of NPR.

Counter-intuitively, the nonlinear terms in the model cannot be considered as nonlinear noise[27]. The concept of correlated component and orthogonal component were proposed in [28]. Orthogonal component means the part of nonlinear output which is orthogonal to the input signal. In some case, the orthogonal component could be considered as nonlinear noise [29]. However, the measurement of orthogonal component is quite challenging because it needs precise comparison of nonlinear input and output waveform [30] . In fact, if we have nonlinear output waveform, we could calculate BER directly.

In short summary, there are lots of open issues about device nonlinear imperfections. One of the most urgent topic is to find a good specification which is high correlated with system performance and could be measured practically.

Conclusions

Device imperfections turn to be the dominant impairment for high speed, high order modulation coherent transceivers. Various methods have been proposed to calibrate the linear imperfections. They could even be self-calibrated with transceiver itself only. The nonlinear imperfections are much more complicated and needs more research. One urgent topic is to find a good nonlinear specification that indicates transmission performance and could be measured practically.

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